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Volume II Final Report Appendices

Composite Propulsion Feedlines For Cryogenic Space Vehicles

by

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16. Abstract

Thin metallic liners that provide leak-free service in cryogenic propulsion systems are overwrapped with a glass-fiber composite that provides strength and protection from handling damage. The resultant tube is lightweight, strong and has a very low thermal flux. Several styles of tubing ranging from 5 to 38 cm (2 to 15 in.) in diameter and up to 305 cm (10 ft) long were fabricated and tested at operating temperatures from 294 to 21 K (+70 to -423°F) and operating pressures up to 259 N/sq cm (375 psi). The primary objective for the smaller sizes was thermal performance optimization of the propulsion system while the primary objective of the larger sizes was weight optimization and to prove fabricability. All major program objectives were met resulting in a design concept that is adaptable to a wide range of aerospace vehicle requirements. Major items of development included bonding large diameter aluminum end fittings to the thin Inconel liner; fabrication of a 38 cm (15 in.) diameter tube from 0.008 cm (0.003 in.) thick Inconel; and evaluation of tubing which provides essentially zero quality propellant in a very short period of time resulting in a lower mass of propellant expended in chilldown.

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FOREWORD

The work described herein was conducted by the Martin Marietta Corporation, Denver Division, under NASA Contract NAS3-14370. Work was done under the management of the NASA Project Manager, Mr. Joseph Notardonato, Liquid Rocket Technology Branch, NASA-Lewis Research Center, Cleveland, Ohio. Messrs. James Faddoul, James Barber and Al Pavli also served as Project Managers during some phases of the contract.

Volume I of this report describes the results of the program and Volume II contains the appendixes related thereto. Volume II, therefore, is subordinate to Volume I.

APPENDIX A

DESIGN BOUNDARY CONDITIONS

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DESIGN BOUNDARY CONDITIONS

A series of boundary conditions was selected and applied to the feedline designs. The boundary conditions selected are presented in Table A-1 for the OMS systems and Table A-2 for the main engine systems. These lists relate to system conditions specified by the Phase B baseline study and the results of the feedline optimization math model output.

TABLE A-1 DESIGN BOUNDARY CONDITIONS -- OMS FEEDLINES

	OMS		ACPS	
	LOX	LH_2	LOX	LH_2
1. GEOMETRY	*	*	*	*
2. CONFIGURATION	*	*	*	*
a. Length	*	*	*	*
b. Diameter	*	*	*	*
c. Wall Thickness				
1. Liner	0.008 cm (0.003 in.)	0.008 cm (0.003 in.)	0.008 cm (0.003 in.)	0.008 cm (0.003 in.)
2. Overwrap	0.051 cm (0.020 in.)	0.051 cm (0.020 in)	0.051 cm (0.020 in.)	0.051 cm (0.020 in.)
3. Weight/cm	+Math Model Output	Math Model Output	Math Model Output	Math Model Output
d. Jacket Thickness				
1. Liner	0.03 cm (0.012 in.) Stainless	0.03 cm (0.012 in.) Stainless	0.07 cm (0.028 in.) Aluminum	0.07 cm (0.028 in.) Aluminum
e. Gimbals/Bellows	NONE	NONE	NONE	NONE
f. Sliding Joints	7	9	NONE	NONE
1. Weight	5.9 kg (13 lb) Total	12.2 kg (27 lb) Total	N/A	N/A

* This information is shown on the design schematics of Appendix "B" or included in the design notes for those schematics.

\+ Math model output is a variable and is included in various sections of this report.

TABLE A-1 DESIGN BOUNDARY CONDITIONS -- OMS FEEDLINES (CONT'D)

	OMS		ACPS	
	LOX	LH_2	LOX	LH_2
g. End Fittings				
1. Type	Conoseal	Conoseal	Conoseal	Conoseal
2. Location	*	*	*	*
3. Weight	32.2 kg (71 lb.) Total	57.7 kg (127 lb) Total	Unknown	Unknown
h. Valves	8	8	Unknown	Unknown
1. Weight	32.2 kg (71 lb.) Total	55.4 kg (122 lb) Total	Unknown	Unknown
3. MATERIAL				
a. Liner	Inconel 718	Inconel 718	Inconel 718	Inconel 718
b. Overwrap	S/HTS Glass-fiber	S/HTS Glass-fiber	S/HTS Glass-fiber	S/HTS Glass-fiber
4. OPERATING CONDITIONS				
a. Flowrate	25.6 kg/sec (56.4 lb/sec)	5.1 kg/sec (11.2 lb/sec)	20.6 kg/sec (45.4 lb/sec)	6.6 kg/sec (14.6 lb/sec)
b. Pressure	45 N/sq cm (65 psi)	31 N/sq cm (45 psi)	34.5 N/sq cm (50 psi)	34.5 N/sq cm (50 psi)
c. Temperature Range	89 to 297K (-300 to 75°F)	21 to 297K (-423 to 75°F)	89 to 297K (-300 to 75°F)	21 to 297K (-423 to 75°F)

TABLE A-1 DESIGN BOUNDARY CONDITIONS -- OMS FEEDLINES (CONT'D)

	OMS		ACPS	
	LOX	LH_2	LOX	LH_2
5. STRUCTURAL				
a. Pressure				
1. Burst/Safety Factor	2	2	2	2
b. "g" Load	3	3	3	3
c. Allowable Stress-Liner	114,100 N/sq cm (165,500 psi)	123,800 N/sq cm (179,500 psi)	114,100 N/sq cm (165,500 psi)	123,800 N/sq cm (179,500 psi)
d. Allowable Stress-Overwrap	20,270 N/sq cm (29,400 psi)	21,300 N/sq cm (30,900 psi)	20,270 N/sq cm (29,400 psi)	21,300 N/sq cm (30,900 psi)
e. Leakage - Allowable	10^{-4} scc/sec He/Joint	10^{-4} scc/sec He/Joint	10^{-4} scc/sec He/Joint	10^{-4} scc/sec He/Joint
f. Operating Pressure Leak Checks	At Ambient Temperature After Fabrication is Complete			
6. THERMAL				
a. Chilldown Technique				
1. Feed System Conditioning	Function of Wet or Dry (Selected Wet)	Function of Wet or Dry (Selected Dry)	Pump & Heat Exchanger	Pump & Heat Exchanger
2. Engine Conditioning	Pumped	Pumped	Pumped	Pumped
3. Insulation	Foam Inside Vacuum Jacket			

TABLE A-1 DESIGN BOUNDARY CONDITIONS -- OMS FEEDLINES (CONCLUDED)

	OMS		ACPS	
	LOX	LH_2	LOX	LH_2
7. STARTS/MISSION	13	13	13	13
8. MISSION DURATION	7 Days Nominal	7 Days Nominal	7 Days Nominal	7 Days Nominal
9. PROPELLANT TANKAGE				
a. Material	2219-T87 Aluminum	2219-T87 Aluminum	2219-T87 Aluminum	2219-T87 Aluminum
b. Thickness	0.132 cm (0.052 in.)	0.090 cm (0.036 in.)	0.102 cm (0.040 in.)	0.102 cm (0.040 in.)
c. Propellant Quantity	18,576 kg (40,867 lb)	4144 kg (9116 lb)	608 kg (1338 lb)	257 kg (565 lb)
d. Pressurization	28 N/sq cm (41 psi)	22 N/sq cm (32 psi)	24 N/sq cm (35 psi)	25 N/sq cm (36 psi)
10. OPERATING LIFE	100 Missions	100 Missions	100 Missions	100 Missions

TABLE A-2 DESIGN BOUNDARY CONDITIONS -- MAIN ENGINE FEEDLINES

	BOOSTER MAIN ENGINE		ORBITER MAIN ENGINE	
	LOX	LH_2	LOX	LH_2
1. GEOMETRY	*	*	*	*
2. CONFIGURATION	*	*	*	*
a. Length	*	*	*	*
b. Diameter	*	*	*	*
c. Wall Thickness				
1. Liner	+Math Model Output	Math Model Output	Math Model Output	Math Model Output
2. Overwrap	+Math Model Output	Math Model Output	Math Model Output	Math Model Output
3. Weight/In.	+Math Model Output	Math Model Output	Math Model Output	Math Model Output
d. Vacuum Jacket Thickness				
1. Liner	N/A	0.053 cm (0.021 in.)	N/A	0.030 cm (0.012 in.)
2. Overwrap	N/A	N/A	N/A	N/A
3. Weight	N/A	47 g/cm (0.2612 lb/in)	N/A	27 g/cm (0.151 lb/in.)
e. Gimbals/Bellows	46 total	36 total	2 Angulation Joints	4 Angulation Joints
1. Location	*	*	*	*
2. Weight	1246 kg (2748 lbs)	482 kg (1062 lbs)	112 kg (248 lb)total	50 kg (110 lb)total
f. Sliding Joints	N/A	N/A	9	2
1. Location	N/A	N/A	*	*
2. Weight	N/A	N/A	131 kg (288 lb)total	11 kg (24 lb)total

+ Math model output is a variable and is included in various sections of this report.

* This information is shown on the design schematics of Appendix "B" or included in the design notes for those schematics.

TABLE A-2 DESIGN BOUNDARY CONDITIONS--MAIN ENGINE FEEDLINES (CONT'D)

	BOOSTER MAIN ENGINE		ORBITER MAIN ENGINE	
	LOX	LH_2	LOX	LH_2
g. End Fittings				
1. Type	Conoseal	Conoseal	Conoseal	Conoseal
2. Location	*	*	*	*
3. Weight	375 kg (826 lbs) Total	212 kg (468 lbs) Total	209 kg (460 lbs) Total	55 kg (121 lbs) Total
h. Valves				
1. Location	*	*	*	*
2. Weight	66 kg (145 lb)/ Valve	66 kg (145 lb)/ Valve	88 kg (195 lb)/ Valve	59 kg (130 lb)/ Valve
3. MATERIAL				
a. Liner	Inconel	Inconel	Inconel	Inconel
b. Overwrap	S-HTS Glass Fibers in 58-68R Resin	S-HTS Glass Fibers in 58-68R Resin	S-HTS Glass Fibers in 58-68R Resin	S-HTS Glass Fibers in 58-68R Resin
4. OPERATING CONDITIONS				
a. Flowrate	583 kg/sec (1286 lbs/ sec) each engine	97 kg/sec (214 lbs/sec) each engine	583 kg/sec (1286 lb/ sec) each engine	97 kg/sec (214 lb/sec) each engine
b. Pressure (design)	260 N/sq cm (375 psi) @ engine	69 N/sq cm (100 psi) @ engine	144 N/sq cm (209 psi) @ engine	25 N/sq cm (36 psi) @ engine
c. Temperature Range	89 to 297K (-300 to 75^{o} F)	21 to 297K (-423 to 75^{o} F)	89 to 297K (-300 to 75^{o} F)	21 to 297K (-423 to 75^{o}F)
5. STRUCTURAL				
a. Allowable Liner Stress	114,100 N/sq cm (165,500 psi)	123,800 N/sq cm (179,500 psi)	114,100 N/sq cm (165,500 psi)	123,800 N/sq cm (179,500 psi)
b. Allowable Overwrap Stress	20,270 N/sq cm (29,400 psi)	21,300 N/sq cm (30,900 psi)	20,270 N/sq cm (29,400 psi	21,300 N/sq cm (30,900 psi)

TABLE A-2 DESIGN BOUNDARY CONDITIONS -- MAIN ENGINE FEEDLINES (CONCLUDED)

	BOOSTER MAIN ENGINE		ORBITER MAIN ENGINE	
	LOX	LH_2	LOX	LH_2
c. Modulus of Elasticity Composite	3.8 x 10^6 N/sq cm (5.5 x 10^6psi)	3.8 x 10^6 N/sq cm (5.5 x 10^6psi)	3.8 x 10^6 N/sq cm (5.5 x 10^6psi)	3.8 x 10^6 N/sq cm (5.5 x 10^6psi)
d. Leakage - Allowable	10^{-4} scc/sec He/Joint	10^{-4} scc/sec He/Joint	10^{-4} scc/sec He/Joint	10^{-4} scc/sec He/Joint
e. Operating Pressure Leak Checks	At Ambient Temperature After Fabrication is Complete			
6. THERMAL				
a. Feed System Conditioning	Natural Circulation	Pumped	Natural Circulation	Pumped
b. Engine Conditioning	Pumped	Pumped	Pumped	Pumped
c. Insulation	None	Foam Inside Vac. Jacket	None	Foam Inside Vac. Jacket
7. START QUALITY PROPELLANT	95K (-289.5°F)	22.6K (-419.3°F)	95K (-289.5°F)	22.6K (-419.3°F)
8. STARTS/MISSION	1	1	1	1
9. MISSION DURATION	194.6 sec.	194.6 sec.	207.8 sec.	207.8 sec.
10. OPERATING LIFE	100 Missions	100 Missions	100 Missions	100 Missions

APPENDIX B

VEHICLE FEEDLINE DESIGN

APPENDIX B

VEHICLE FEEDLINE DESIGN

Selected Systems. - Concurrent with the analysis activities the Phase B baseline study was reviewed for specific OMS, ACPS, and main engine propulsion feedline configurations. Configuration layouts of the twelve candidate systems are shown in Figure B-1 through B-12, and the detail specifications including lengths and diameters are shown in Tables B-1 through B-12. The work performed does not include finalized detailed designs of the feedline systems but rather conceptual designs sufficient to determine the configuration, including bends, size, length, etc., and the location of pumps, engines, tanks, etc.

Candidate systems were chosen as those systems which afforded the largest total system weight savings, including consumables, and met the temperature and pressure constraints for composite lines as developed under NAS3-12047.

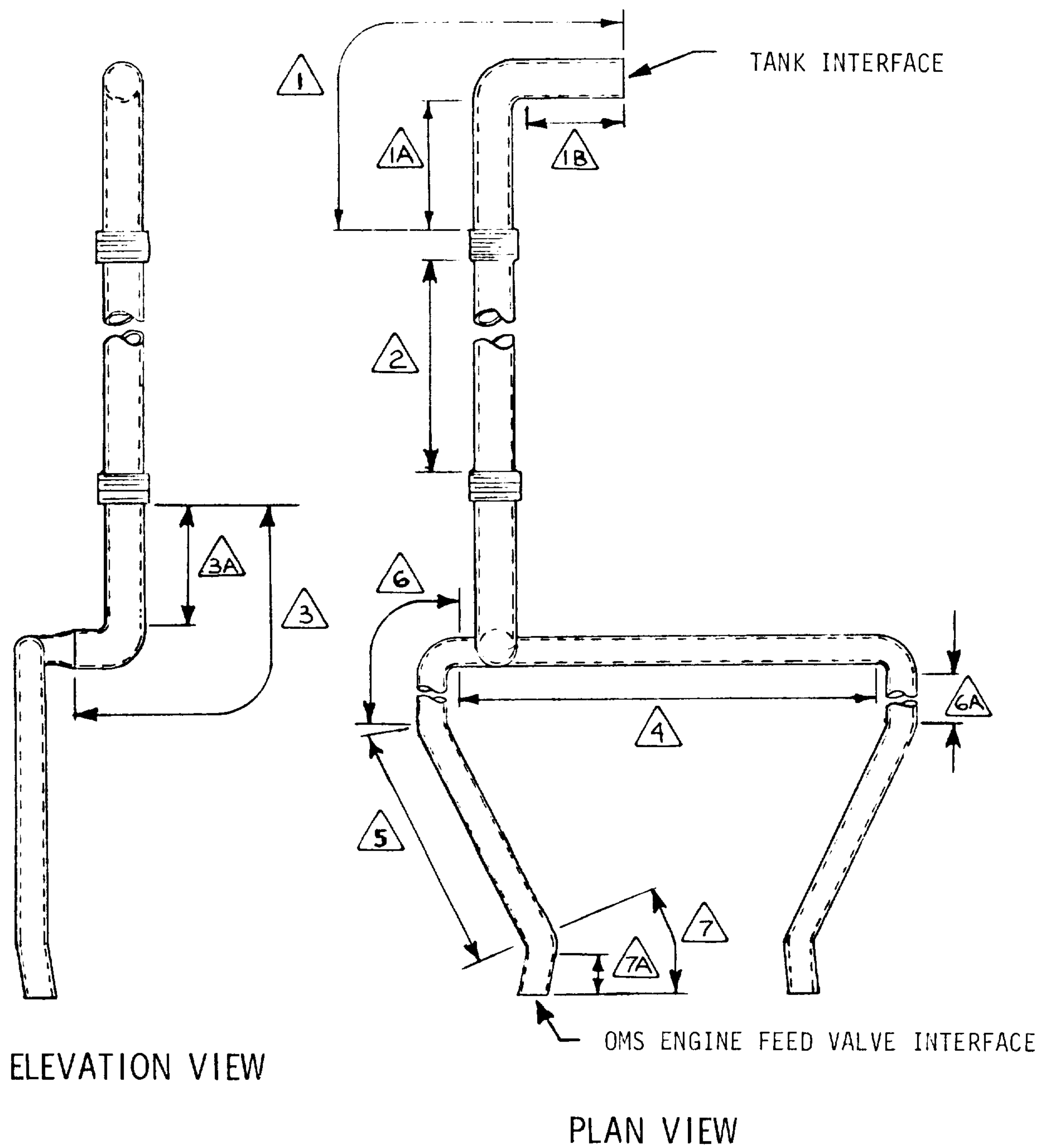


Figure B-1. - Orbiter OMS LH_2 Feedline

TABLE B-1. - ORBITER OMS LH_2 FEEDLINE

1. 546 cm (215 in.) long, 9.9 cm (3.9 in.) dia., 0.05 cm (0.02 in.) wall, stainless steel inside line.
546 cm (215 in.) long, 18.5 cm (7.3 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket.

1A. 394 cm (155 in.) long, straight section.

1B. 137 cm (54 in.) long, straight section.

2. 1460 cm (575 in.) long, 9.9 cm (3.9 in.) dia., 0.05 cm (0.02 in.) wall, stainless steel inside line.
1460 cm (575 in.) long, 18.5 cm (7.3 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket.

3. 419 cm (165 in.) long, 9.9 cm (3.9 in.) dia., 0.05 cm (0.02 in.) wall, stainless steel inside line.
419 cm (165 in.) long, 18.5 cm (7.3 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket.

3A. 345 cm (136 in.) long, straight section.

4. 681 cm (268 in.) long, 7.9 cm (3.1 in.) dia., 0.05 cm (0.02 in.) wall, stainless steel inside line.
681 cm (268 in.) long, 15.8 cm (6.2 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket.

5. 335 cm (132 in.) long, 7.9 cm (3.1 in.) dia., 0.05 cm (0.02 in.) wall, stainless steel inside line typical 2 plcs.
335 cm (132 in.) long, 15.8 cm (6.2 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket typical 2 plcs.

6. 267 cm (105 in.) long, 7.9 cm (3.1 in.) dia., 0.05 cm (0.02 in.) wall, stainless steel inside line typical 2 plcs.
267 cm (105 in.) long, 15.8 cm (6.2 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket typical 2 plcs.

6A. 226 cm (89 in.) long, straight section typical 2 plcs.

7. 69 cm (27 in.) long, 7.9 cm (3.1 in.) dia., 0.05 cm (0.02 in.) wall stainless steel inside line typical 2 plcs.
69 cm (27 in.) long, 15.8 cm (6.2 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket typical 2 plcs.

7A. 51 cm (20 in.) long, straight section, typical 2 plcs.

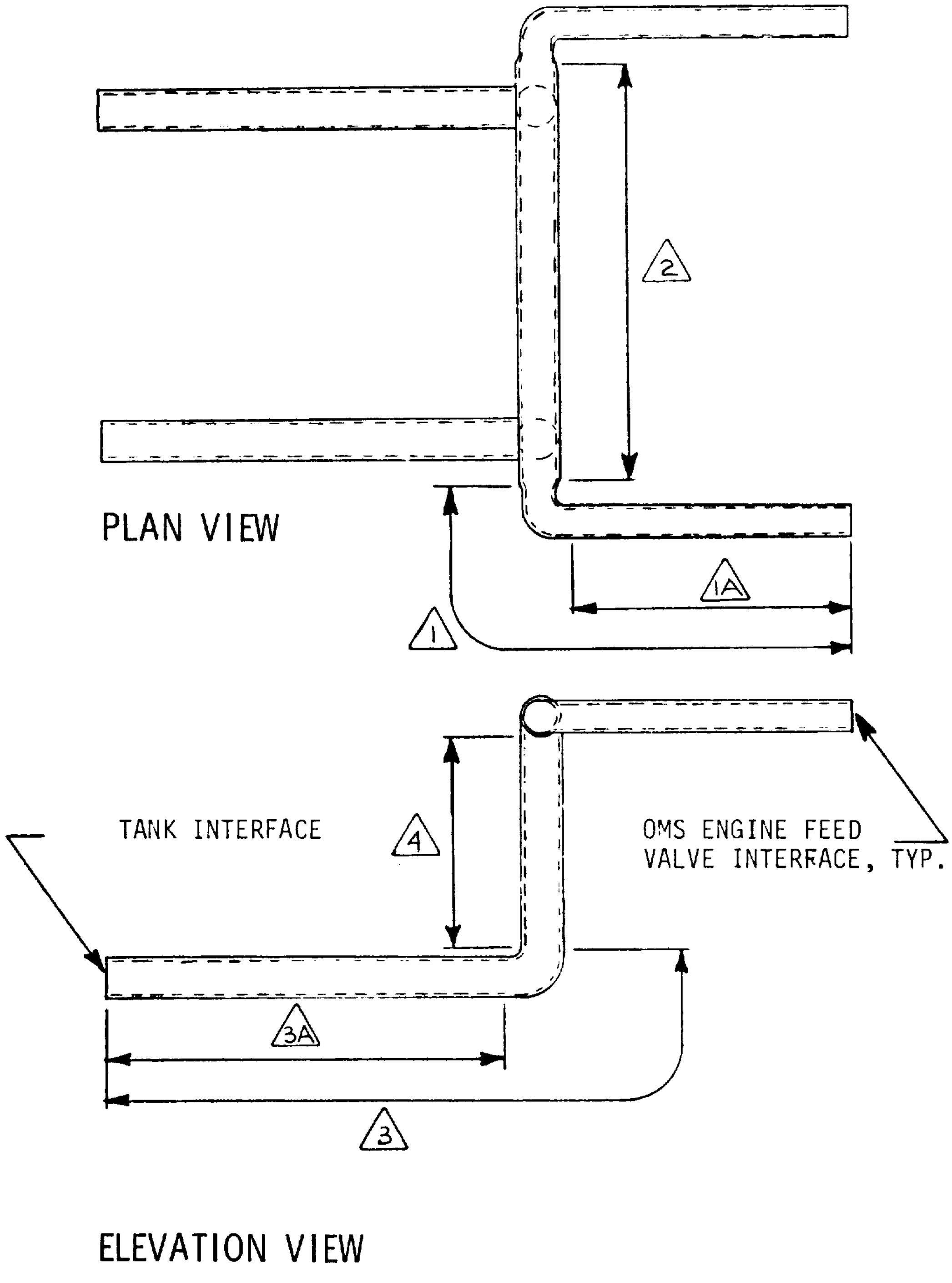


Figure B-2. - Orbiter OMS LOX Feedline

TABLE B-2. - ORBITER OMS LOX FEEDLINE

1 140 cm (55 in.) long, 5.5 cm (2.15 in.) dia., 0.041 cm (0.016 in.) wall, stainless steel inside line typical 2 plcs.
140 cm (55 in.) long, 13.2 cm (5.2 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket typical 2 plcs.

1A 114 cm (45 in.) long, straight section, typical 2 plcs.

2 381 cm (150 in.) long, 6.7 cm (2.65 in.) dia., 0.041 cm (0.016 in.) wall, stainless steel inside line.
381 cm (150 in.) long, 15 cm (5.9 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket.

3 241 cm (95 in.) long, 6.7 cm (2.65 in.) dia., 0.041 cm (0.016 in.) wall, stainless steel inside line, typical 2 plcs.
241 cm (95 in.) long, 15 cm (5.9 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket, typical 2 plcs.

3A 178 cm (70 in.) long, straight section, typical 2 plcs.

4 135 cm (53 in.) long, 6.7 cm (2.65 in.) dia., 0.041 cm (0.016 in.) wall, stainless steel inside line, typical 2 plcs.
135 cm (53 in.) long, 15 cm (5.9 in.) dia., 0.03 cm (0.012 in.) wall, stainless steel jacket, typical 2 plcs.

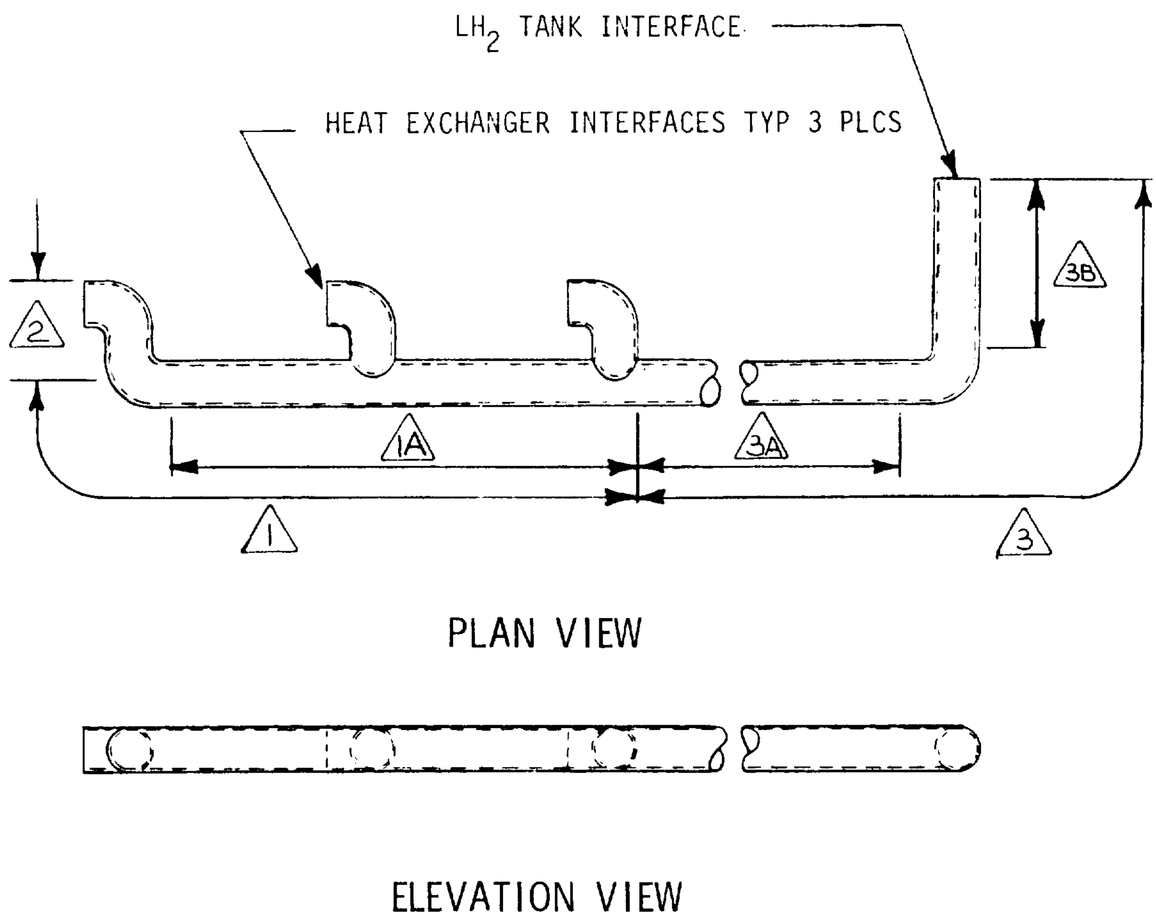


Figure B-3. - Orbiter ACPS LH_2 Feedline

TABLE B-3. - ORBITER ACPS LH_2 FEEDLINE

1 — 279 cm (110 in.) long, 3.63 cm (1.43 in.) dia., 0.07 cm (0.028 in.) wall, aluminum inside line.
279 cm (110 in.) long, 9.53 cm (3.75 in.) dia., 0.07 cm (0.028 in.) wall, aluminum jacket.

1A — 254 cm (100 in.) long, straight section.

2 — 30 cm (12 in.) long, 3.63 cm (1.43 in.) dia., 0.07 cm (0.028 in.) wall, aluminum inside line, typical 3 plcs.
30 cm (12 in.) long, 9.53 cm (3.75 in.) dia., 0.07 cm (0.028 in.) wall, aluminum jacket, typical 3 plcs.

3 — 546 cm (215 in.) long, 3.63 cm (1.43 in.) dia., 0.07 cm (0.028 in.) wall, aluminum inside line.
546 cm (215 in.) long, 9.53 cm (3.75 in.) dia., 0.07 cm (0.028 in.) wall, aluminum jacket.

3A — 457 cm (180 in.) long, straight section.

4 — 56 cm (22 in.) long, straight section.

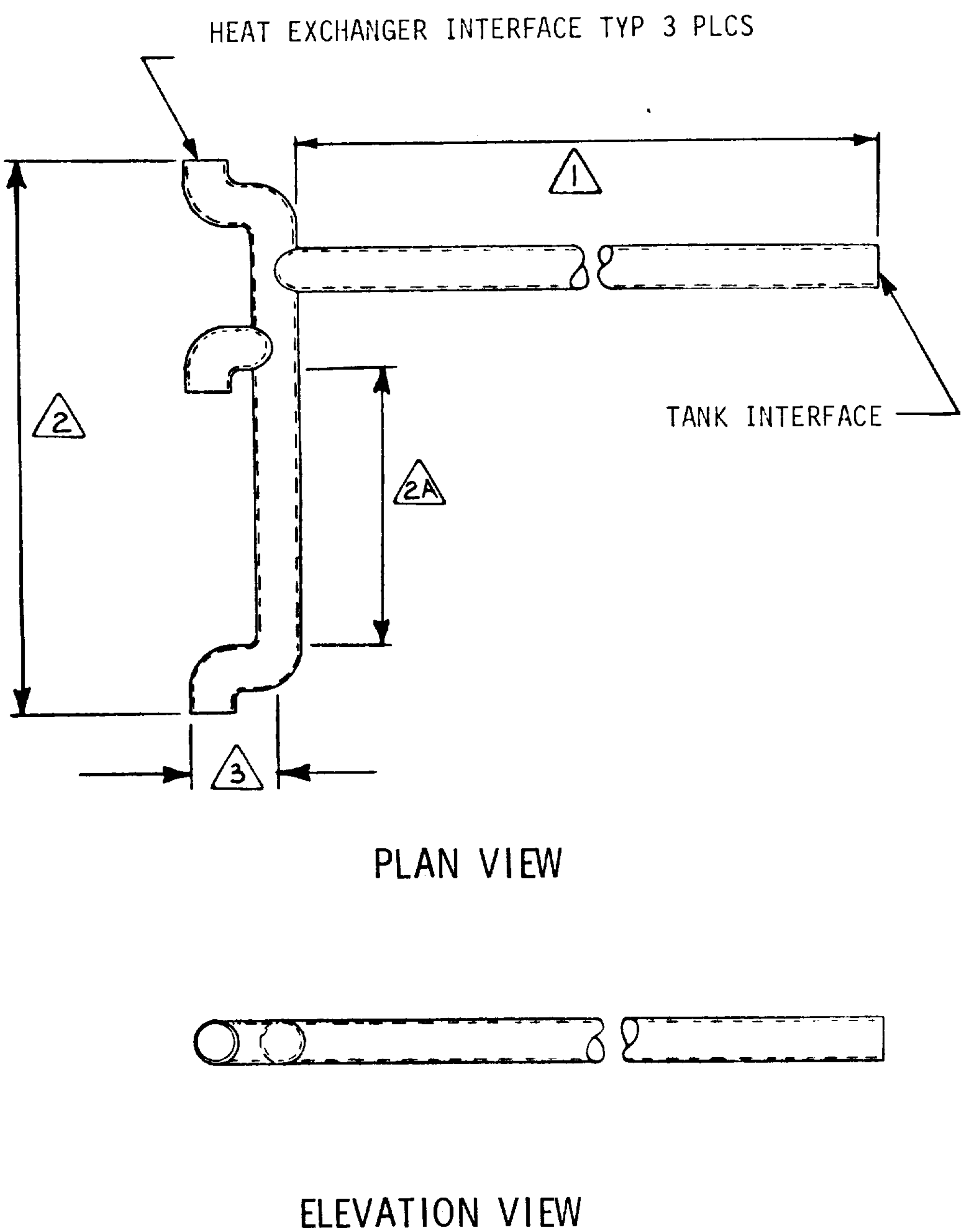


Figure B-4. - Orbiter ACPS LOX Feedline

TABLE B-4. - ORBITER ACPS LOX FEEDLINE

△1 508 cm (200 in.) long, 2.95 cm (1.16 in.) dia., 0.07 cm (0.028 in.) wall aluminum inside line.
508 cm (200 in.) long, 8.51 cm (3.35 in.) dia., 0.07 cm (0.028 in.) wall aluminum jacket.

△2 165 cm (65 in.) long, 2.95 cm (1.16 in.) dia., 0.07 cm (0.028 in.) wall aluminum inside line.
165 cm (65 in.) long, 8.51 cm (3.35 in.) dia., 0.07 cm (0.028 in.) wall aluminum jacket.

△2A 79 cm (31 in.) long straight section.

△3 21.6 cm (8.5 in.) long, 2.95 cm (1.16 in.) dia., 0.07 cm (0.028 in.) wall aluminum inside line. Typical 3 plcs.
21.6 cm (8.5 in.) long, 8.51 cm (3.35 in.) dia., 0.07 cm (0.028 in.) wall aluminum jacket. Typical 3 plcs.

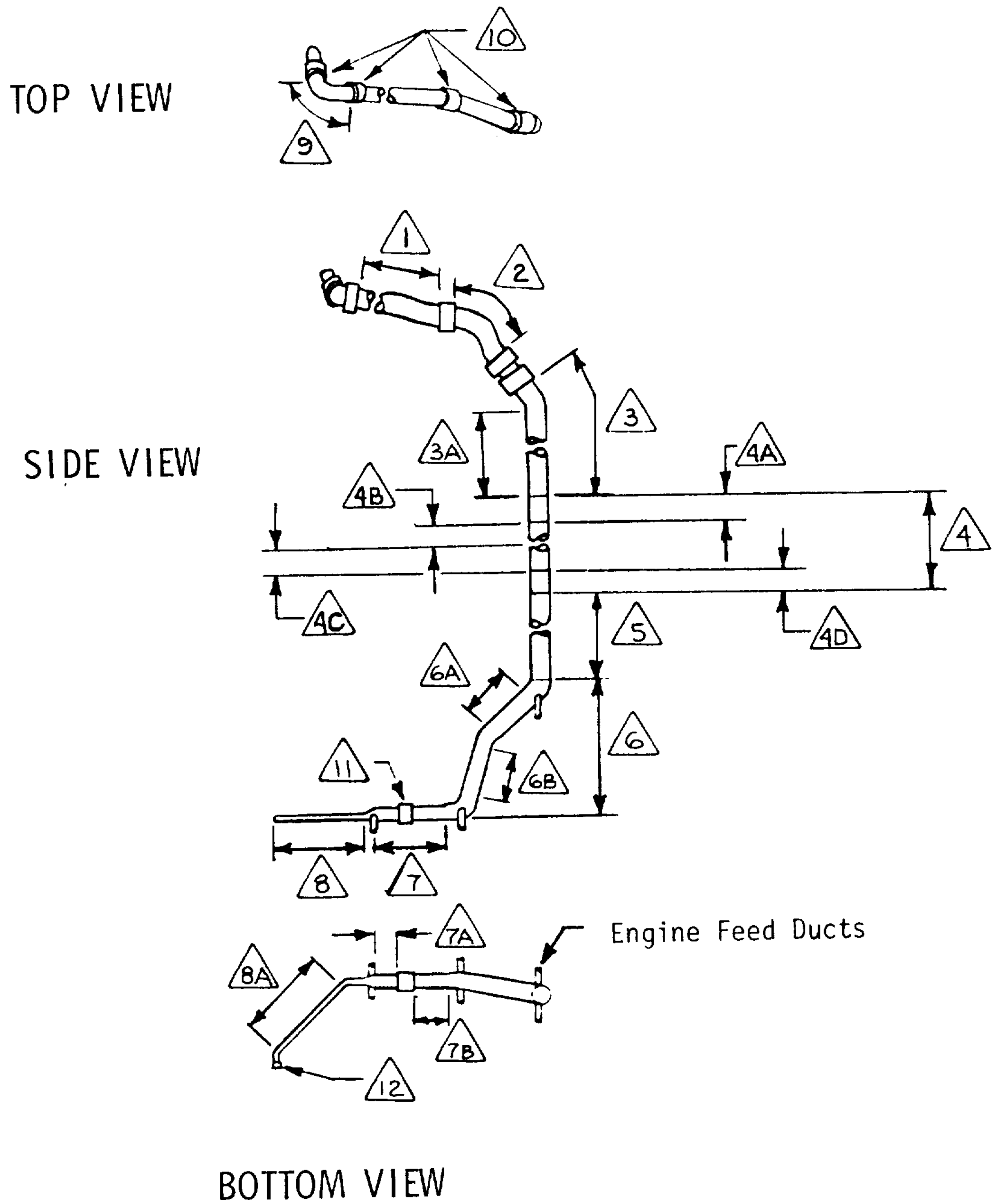


Figure B-5. - Booster LOX Main Engine Feedline

TABLE B-5. - BOOSTER LOX MAIN FEEDLINE

(Quantities shown are for one main feedline only. The other main feedline is symmetrical.)

△1 325 cm (128 in.) long, 56 cm (22 in.) dia., 0.16 cm (0.063 in.) wall, stainless steel.

△2 142 cm (56 in.) long, 56 cm (22.0 in.) dia., 0.16 cm (0.063 in.) wall, stainless steel.

△3 457 cm (180.0 in.) long, 56 cm (22.0 in.) dia., 0.20 cm (0.080 in.) wall, aluminum.

△3A 305 cm (120.0 in.) long, straight.

△4 2438 cm (960.0 in.) long, 56 cm (22.0 in.) dia., 0.2 cm (0.080 in.) wall, aluminum (4 each 240.0 sections).

△5 610 cm (240.0 in.) long, 56 cm (22.0 in.) dia., 0.23 cm (0.092 in.) wall, aluminum.

△6 419 cm (165.0 in.) long, 56 cm (22.0 in.) dia., 0.32 cm (0.125 in.) wall, stainless steel.

△6A 152 cm (60.0 in.) long, straight.

△6B 152 cm (60.0 in.) long, straight.

△7 241 cm (95.0 in.) long, 33 cm (13.0 in.) dia., 0.20 cm (0.080 in.) wall, stainless steel.

△7A 89 cm (35.0 in.) long, straight.

△7B 89 cm (35.0 in.) long, straight.

△8 432 cm (170.0 in.) long, 20 cm (8.0 in.) dia., 0.11 cm (0.045 in.) wall, stainless steel.

△8A 330 cm (130.0 in.) long, straight.

△9 97 cm (38.0 in.) long, 56 cm (22.0 in.) dia., 0.16 cm (0.063 in.) wall, stainless steel.

△10 5 each, 56 cm (22.0 in.) dia., bellows.

△11 1 each, 33 cm (13.0 in.) dia., bellows.

△12 1 each, 20 cm (8.0 in.) dia., bellows.

Unless otherwise noted, sections shown curved have no significant straight length.

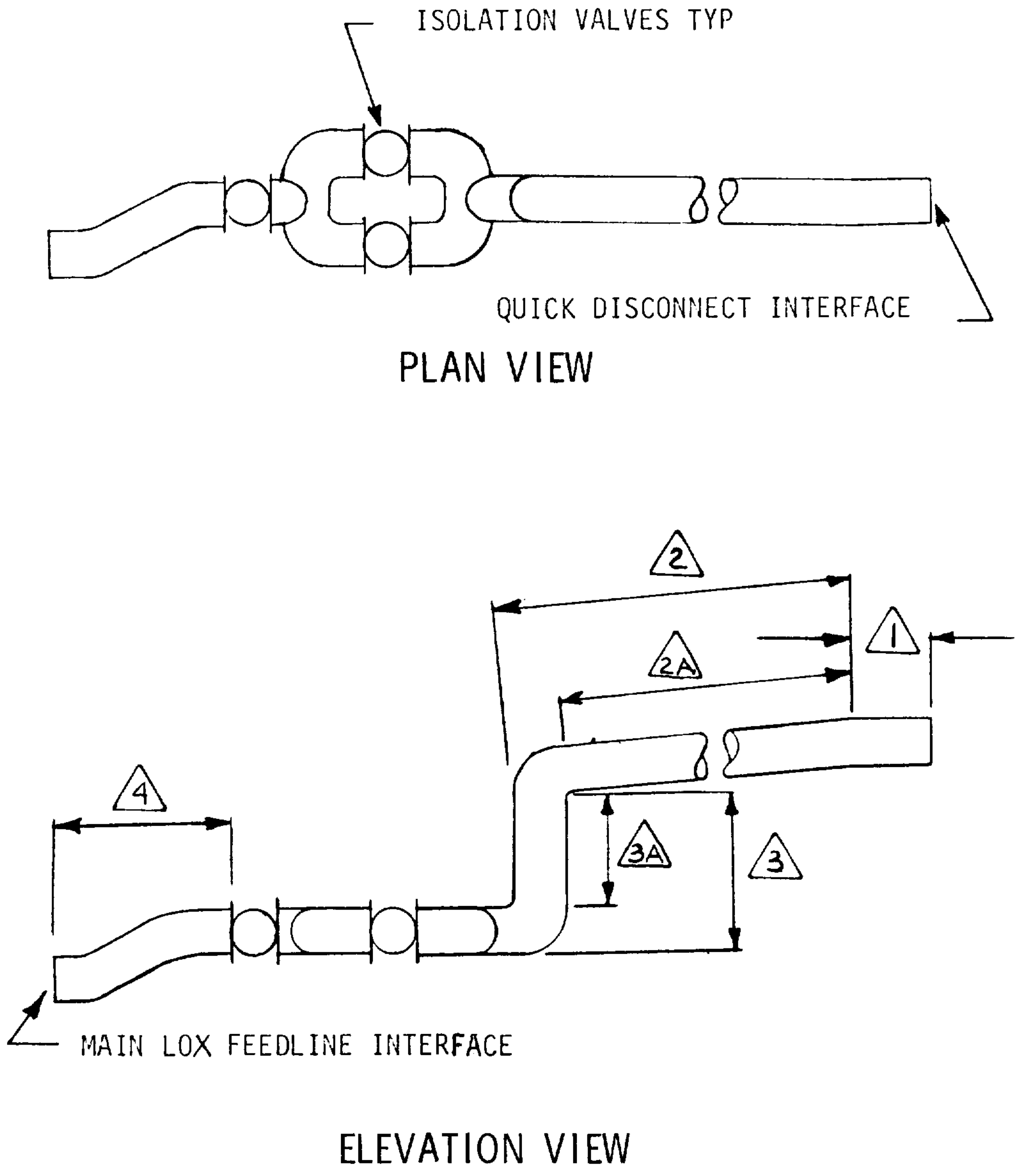


Figure B-6. - Booster LOX Fill and Drain

TABLE B-6. - BOOSTER LOX FILL & DRAIN

1 76 cm (30.0 in.) long, 25 cm (10.0 in.) dia., 0.09 cm (0.035 in.) wall, stainless steel.

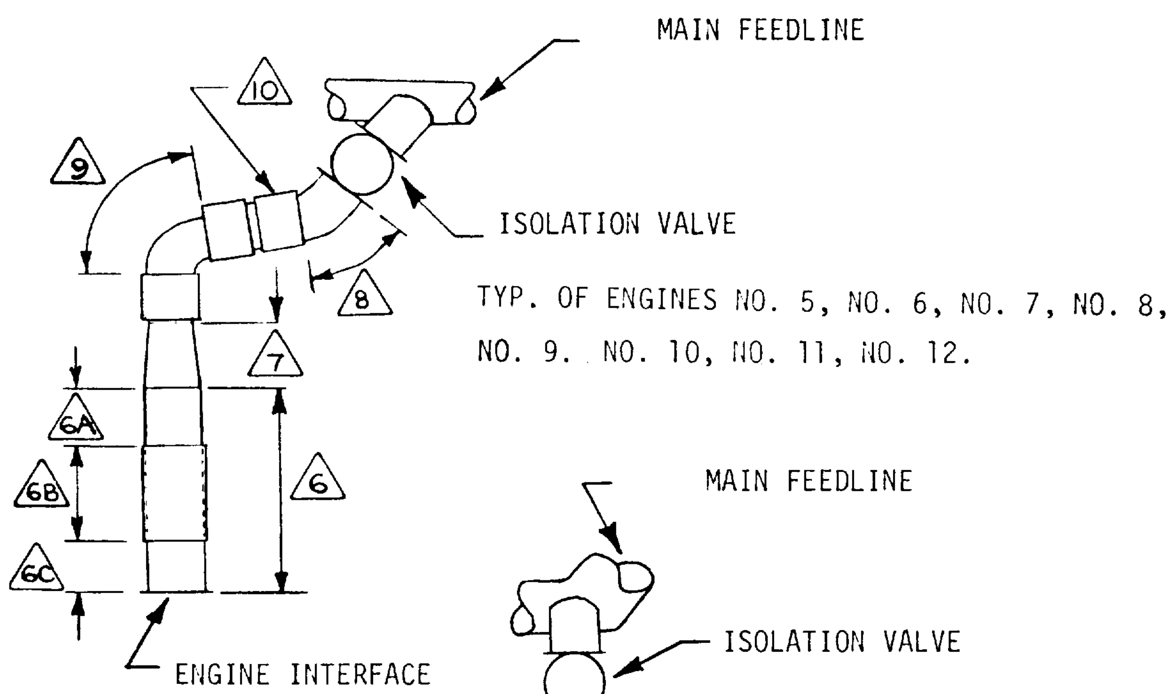
2 269 cm (106.0 in.) long, 25 cm (10.0 in.) dia., 0.09 cm (0.035 in.) wall, stainless steel.

2A 234 cm (92.0 in.) long, straight section.

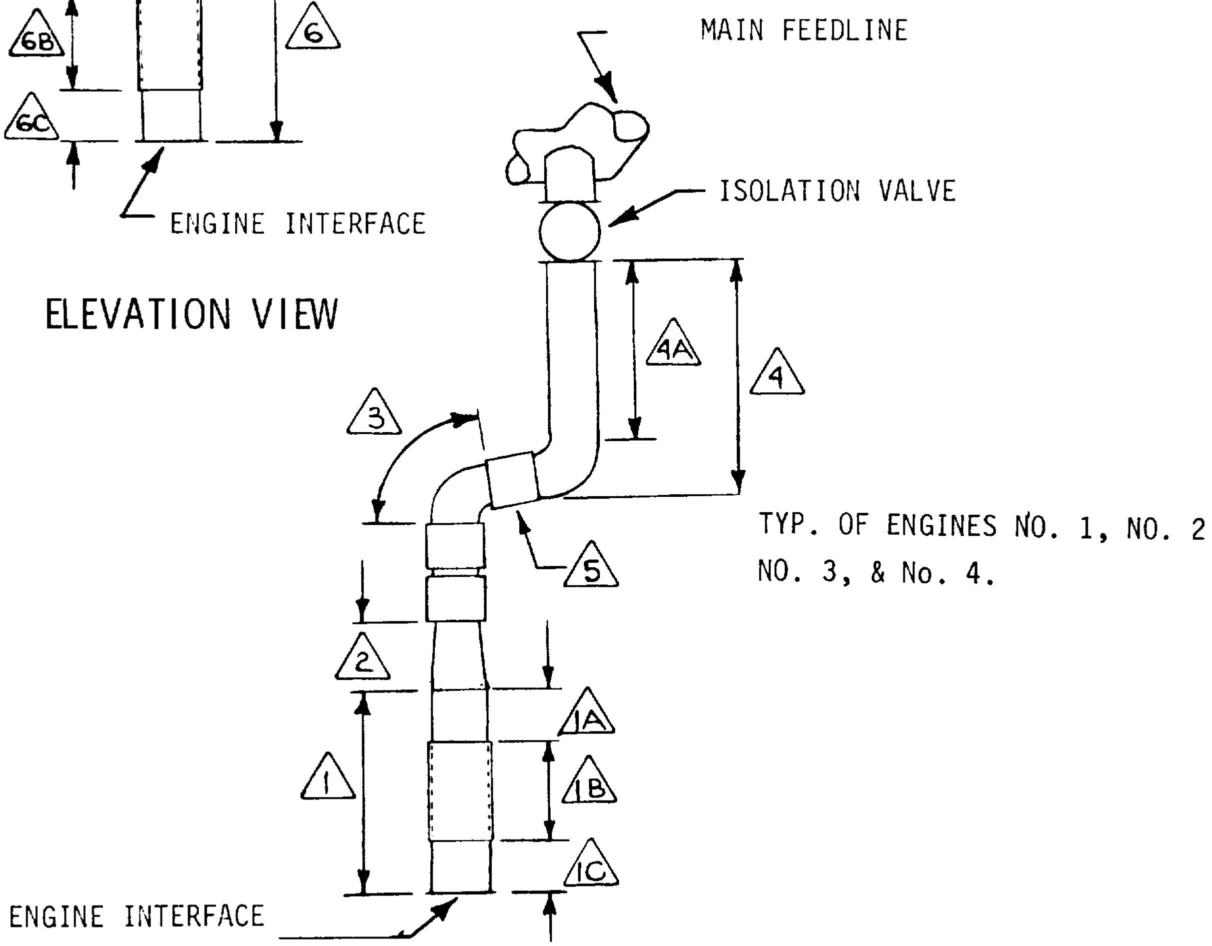
3 127 cm (50.0 in.) long, 25 cm (10.0 in.) dia., 0.09 cm (0.035 in.) wall, stainless steel.

3A 91 cm (36.0 in.) long, straight section.

4 61 cm (24.0 in.) long, 25 cm (10.0 in.) dia., 0.09 cm (0.035 in.) wall, stainless steel.



ELEVATION VIEW



ELEVATION VIEW

Figure B-7. - Booster Main LOX Feed Ducts

TABLE B-7. - BOOSTER MAIN LOX FEED DUCTS

[Engines No. 1, No. 2, No. 3, & No. 4]

△1 142 cm (56.0 in.) long, 38 cm (15.0 in.) dia., 0.20 cm (0.080 in.) wall, stainless steel.

△1A 19 cm (7.5 in.) long, 38 cm (15.0 in.) dia., above accumulator ref.

△1B 85 cm (33.5 in.) long, 46 cm (18.0 in.) dia., accumulator.

△1C 38 cm (15.0 in.) long, 38 cm (15.0 in.) dia., (ref.)

△2 43 cm (17.0 in.) long, 38 cm (15.0 in.) dia to 30 cm (12.0 in.) dia reducer, 0.20 cm (0.080 in.) wall, stainless steel.

△3 91 cm (36.0 in.) long, 30 cm (12.0 in.) dia., 0.16 cm (0.063 in.) wall, stainless steel.

△4 No. 1 and No. 4, 213 cm (84.0 in.) long, 30 cm (12 in.) dia., 0.16 cm (0.063 in.) wall, stainless steel.

△4A No. 1 and No. 4, 132 cm (52.0 in.) long straight.

△4 No. 2 and No. 3, 183 cm (72.0 in.) long, 30 cm (12 in.) dia., 0.16 cm (0.063 in.) wall, stainless steel.

△4A No. 2 and No. 3, 102 cm (40.0 in.) long straight.

△5 3 each, 30 cm (12.0 in.) long, 30 cm (12.0 in.) dia., bellows.

[Engines No. 5, No. 6, No. 7, No. 8, No. 9, No. 10, No. 11 & No. 12]

△6 142 cm (56.0 in.) long, 38 cm (15.0 in.) dia., 0.20 cm (0.080 in.) wall, stainless steel.

△6A 19 cm (7.5 in.) long, 38 cm (15.0 in.) dia., above accumulator.

△6B 85 cm (33.5 in.) long, 46 cm (18.0 in.) dia., accumulator.

△6C 38 cm (15.0 in.) long, 38 cm (15.0 in.) dia.

△7 43 cm (17.0 in.) long, 38 cm (15.0 in.) dia. to 30 cm (12.0 in.) dia. reducer 0.20 cm (0.080 in.) wall, stainless steel.

△8 48 cm (19.0 in.) long, 30 cm (12.0 in.) dia., 0.16 cm (0.063 in.) wall stainless steel.

△9 91 cm (36.0 in.) long, 30 cm (12.0 in.) dia., 0.16 cm (0.063 in.) wall, stainless steel.

△10 3 each, 30 cm (12.0 in.) long, 30 cm (12.0 in.) dia., bellows.

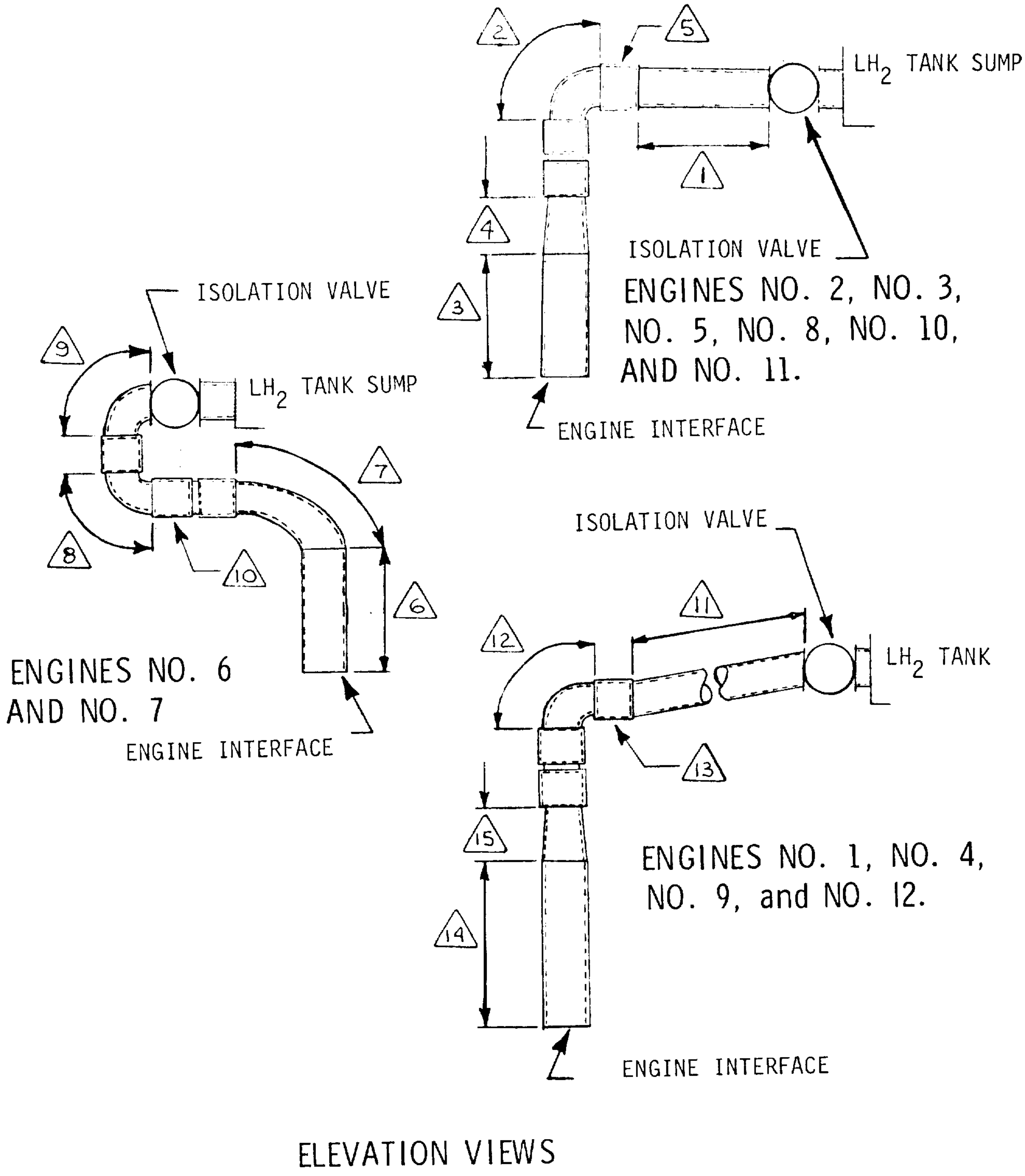


Figure B-8. - Booster Main LH_2 Feed Ducts

TABLE B-8. - BOOSTER MAIN LH_2 FEED DUCTS

[Engines No. 2, No. 3, No. 5, No. 8, No. 10, and No. 11]

1 No. 2 & No. 3 only: 94 cm (37.0 in.) long, 30 cm (12.0 in.) dia. duct, 36 cm (14.0 in.) dia. jacket.
0.09 cm (0.036 in.) wall duct: 0.05 cm (0.021 in.) wall jacket, both stainless steel.

1 No. 5 & No. 8 only: 145 cm (57.0 in.) long, 30 cm (12.0 in.) dia. duct, 36 cm (14.0 in.) dia. jacket.
0.09 cm (0.036 in.) wall duct: 0.05 cm (0.021 in.) wall jacket, both stainless steel.

1 No. 10 and No. 11 only: 81 cm (32.0 in.) long, 30 cm (12.0 in.) dia duct, 36 cm (14.0 in.) dia jacket.
0.09 cm (0.036 in.) wall duct: 0.050 cm (0.021 in.) wall jacket, both stainless steel.

2 81 cm (32.0 in.) long 30 cm (12.0 in.) dia duct, 36 cm (14.0 in.) dia. jacket, 0.09 cm (0.036 in.) wall duct: 0.05 cm (0.021 in.) wall jacket, both stainless steel.

3 102 cm (40.0 in.) long, 38 cm (15.0 in.) dia. duct., 43 cm (17.0 in.) dia. jacket. 0.10 cm (0.040 in.) wall duct: 0.05 cm (0.021 in.) wall jacket, both stainless steel.

4 43 cm (17.0 in.) long, 38 cm (15.0 in.) dia. to 30 cm (12.0 in) dia. reducing duct.
43 cm (17.0 in.) dia. to 36 cm (14.0 in.) dia. reducing jacket.
0.10 cm (0.040 in.) wall duct: 0.05 cm (0.021 in.) wall jacket, both stainless steel.

5 3 each, 30 cm (12.0 in.) long jacketed bellows. 30 cm (12.0 in.) dia., 36 cm (14.0 in.) dia., jacket.

[Engines No. 6 & No. 7]

6 102 cm (40.0 in.) long, 38 cm (15.0 in.) dia., duct, 43 cm (17.0 in.) dia. jacket 0.10 cm (0.040 in.) wall duct;
0.05 cm (0.021 in.) wall jacket both stainless steel.

7 102 cm (40.0 in.) long, 38 cm (15.0 in.) dia to 30 cm (12.0 in.) dia. reducing duct. 43 cm (17.0 in.) dia. to 36 cm (14.0 in.) reducing jacket.
0.10 cm (0.040 in.) wall duct; 0.05 cm (0.021 in.) wall jacket, both stainless steel.

8 and 9 81 cm (32.0 in.) long, 30 cm (12.0 in.) dia. duct., 36 cm (14.0 in.) dia and jacket. 0.09 cm (0.036 in.) wall duct;
0.05 cm (0.021 in.) wall jacket, both stainless steel.

10 3 each, 30 cm (12.0 in.) long, jacketed bellows. 30 cm (12.0 in.) dia., 36 cm (14.0 in.) dia. jacket.

TABLE B-8 BOOSTER MAIN LH_2 FEED DUCTS (CONCLUDED)

[Engines No. 1, No. 4, No. 9 & No. 12]

11 No. 1 & No. 4 only: 114 cm (45.0 in.) long, 30 cm (12.0 in.) dia. duct, 36 cm (14.0 in.) dia. jacket.
0.09 cm (0.036 in.) wall duct: 0.05 cm (0.021 in.) wall jacket, both stainless steel.

11 No. 9 & No. 12 only: 89 cm (35.0 in.) long, 30 cm (12.0 in.) dia. duct. 36 cm (14.0 in.) dia. jacket, 0.09 cm (0.036 in.) wall duct: 0.05 cm (0.021 in.) wall jacket, both stainless steel.

12 81 cm (32.0 in.) long, 30 cm (12.0 in.) dia duct., 36 cm (14.0 in.) dia. jacket, 0.09 cm (0.036 in.) wall duct:
0.05 cm (0.021 in.) wall jacket, both stainless steel.

13 3 each, 30 cm (12.0 in.) long jacketed bellows. 30 cm (12.0 in.) dia., 36 cm (14.0 in.) dia. jacket.

14 142 cm (56.0 in.) long, 38 cm (15.0 in.) dia. duct, 43 cm (17.0 in.) dia jacket. 0.10 cm (0.040 in.) wall duct, 0.05 cm (0.021 in.) wall jacket, both stainless steel.

15 43 cm (17.0 in.) long, 38 cm (15.0 in.) dia. to 30 cm (12.0 in.) dia. reducing duct.
43 cm (17.0 in.) dia to 36 cm (14.0 in.) dia. reducing jacket.
0.10 cm (0.040 in.) wall duct: 0.05 cm (0.021 in.) wall jacket: both stainless steel.

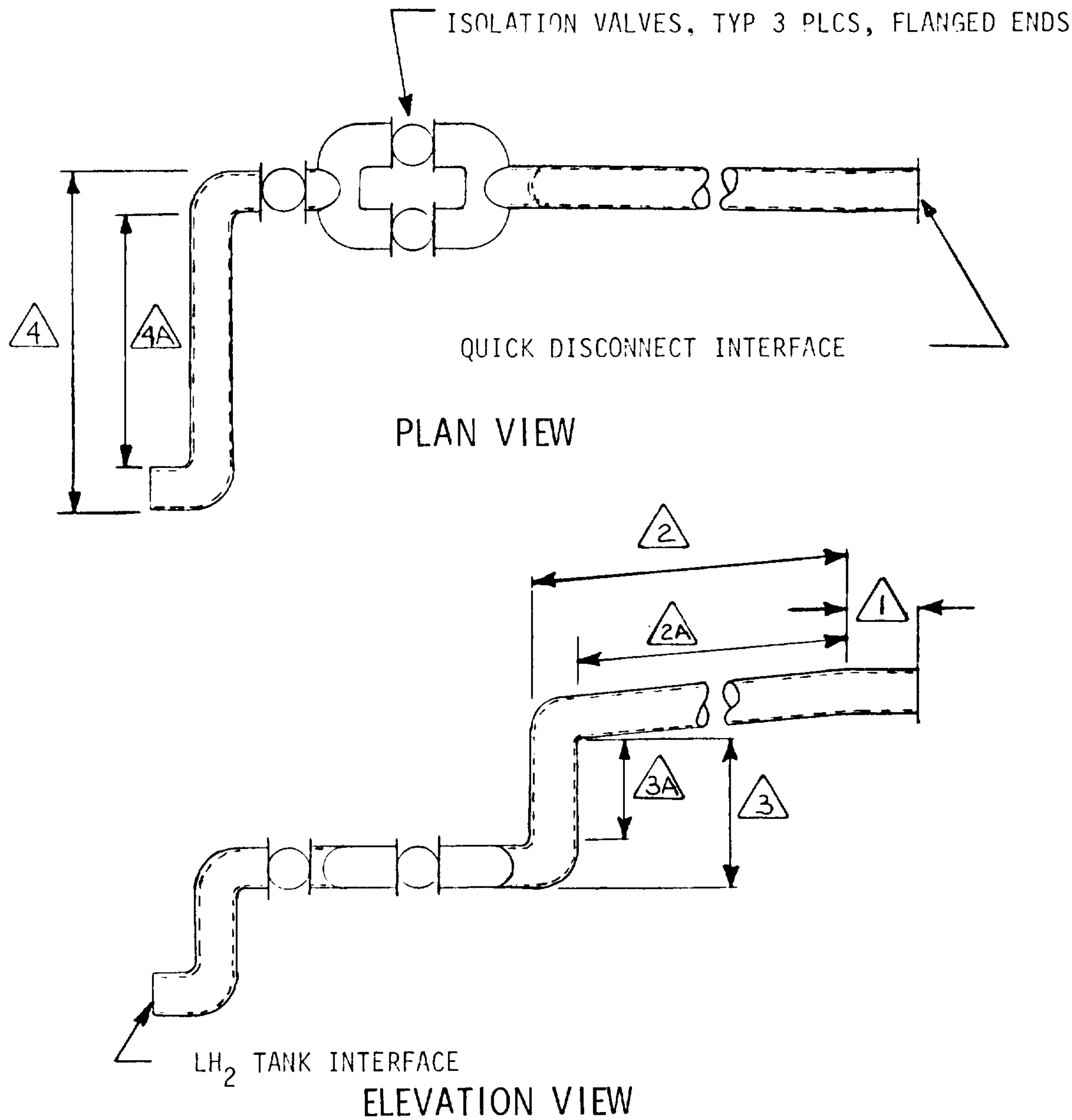


Figure B-9. - Booster LH_2 Fill and Drain

TABLE B-9. - BOOSTER LH_2 FILL AND DRAIN

1 — 76 cm (30.0 in.) long, 25 cm (10.0 in.) dia., 0.08 cm (0.032 in.) wall inner line, stainless steel.
76 cm (30.0 in.) long, 30 cm (12.0 in.) dia., 0.05 cm (0.021 in.) wall, jacket stainless steel.

2 — 269 cm (106.0 in.) long, 25 cm (10.0 in.) dia., 0.08 cm (0.032 in.) wall, inner line stainless steel.
269 cm (106.0 in.) long, 30 cm (12.0 in.) dia., 0.05 cm (0.021 in.) wall, jacket stainless steel.

2A — 229 cm (90.0 in.) straight section.

3 — 127 cm (50.0 in.) long, 25 cm (10.0 in.) dia., 0.08 cm (0.032 in.) wall, inner line, stainless steel.
127 cm (50.0 in.) long, 30 cm (12.0 in.) dia., 0.05 cm (0.021 in.) wall, jacket stainless steel.

3A — 91 cm (36.0 in.) straight section.

4 — 239 cm (94.0 in.) long, 25 cm (10.0 in.) dia., 0.08 cm (0.032 in.) wall, inner line stainless steel.
239 cm (94.0 in.) long, 30 cm (12.0 in.) dia., 0.05 cm (0.021 in.) wall, jacket stainless steel.

4A — 203 cm (80.0 in.) straight section.

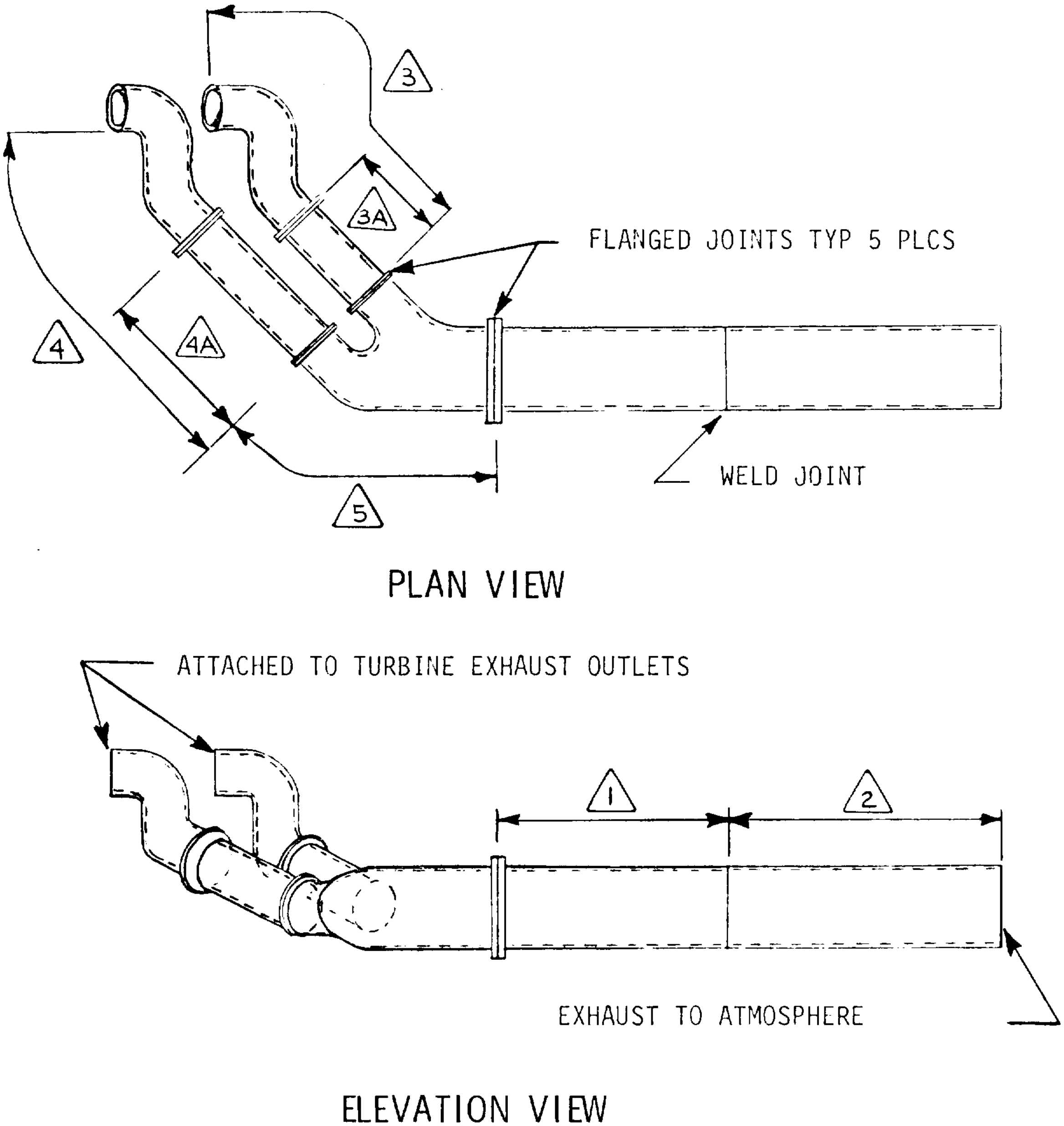


Figure B-10. - Booster Auxillary Power Unit Exhaust Ducts

TABLE B-10. - BOOSTER AUXILLARY POWER UNIT EXHAUST DUCTS

1 203 cm (80.0 in.) long, 51 cm (20.0 in.) dia., 0.10 cm (0.040 in.) wall titanium, outside.
203 cm (80.0 in.) long, 43 cm (17.0 in.) dia., 0.10 cm (0.040 in.) wall stainless steel, inside.

2 127 cm (50.0 in.) long, 51 cm (20.0 in.) dia., 0.10 cm (0.040 in.) wall stainless steel, outside.
127 cm (50.0 in.) long, 43 cm (17.0 in.) dia., 0.10 cm (0.040 in.) wall stainless steel, inside.

3 203 cm (80.0 in.) long, 36 cm (14.0 in.) dia., 0.09 cm (0.035 in.) wall titanium, outside.
203 cm (80.0 in.) long, 29 cm (11.5 in.) dia., 0.08 cm (0.030 in.) wall stainless steel, inside.

3A 102 cm (40.0 in.) straight section.

4 229 cm (90.0 in.) long, 36 cm (14.0 in.) dia., 0.09 cm (0.035 in.) wall titanium, outside.
229 cm (90.0 in.) long, 29 cm (11.5 in.) dia., 0.08 cm (0.030 in.) wall stainless steel, inside.

4A 127 cm (50.0 in.) straight section.

5 102 cm (40.0 in.) long reducing "Y"

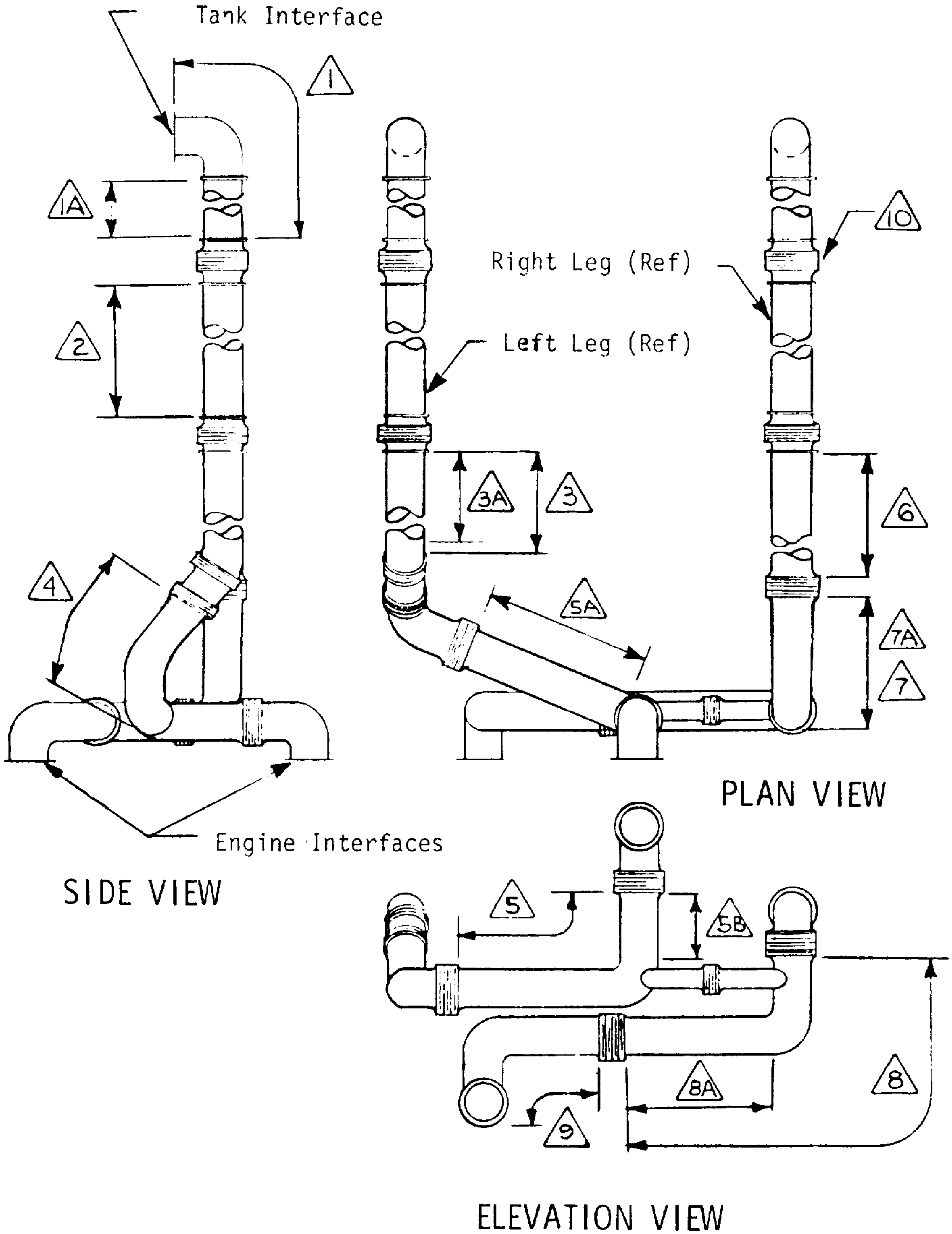


Figure B-11.- Orbiter LOX Main Feedline

TABLE B-11. - ORBITER LOX MAIN FEEDLINES

1 — 889 cm (350.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050) wall aluminum, typ right and left leg.

1A — 808 cm (318.0 in.) long, straight section, typ right and left leg.

2 — 808 cm (318.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall aluminum, typ right and left leg.

3 — 508 cm (200.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall aluminum, left leg only.

3A — 478 cm (188.0 in.) long, straight section.

4 — 122 cm (48.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, left leg only.

5 — 320 cm (126.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, left leg only.

5A — 229 cm (90.0 in.) long, straight section.

5B — 46 cm (18.0 in.) long, straight section.

6 — 508 cm (200.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall aluminum, right leg only.

7 — 173 cm (68.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, right leg only.

7A — 132 cm (52.0 in.) long, straight section.

8 — 203 cm (80.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, right leg only.

8A — 132 cm (52.0 in.) long, straight section.

9 — 163 cm (64.0 in.) long, 46 cm (18.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, right leg only.

10 — 46 cm (18.0 in.) dia., bellows typ 11 plcs.

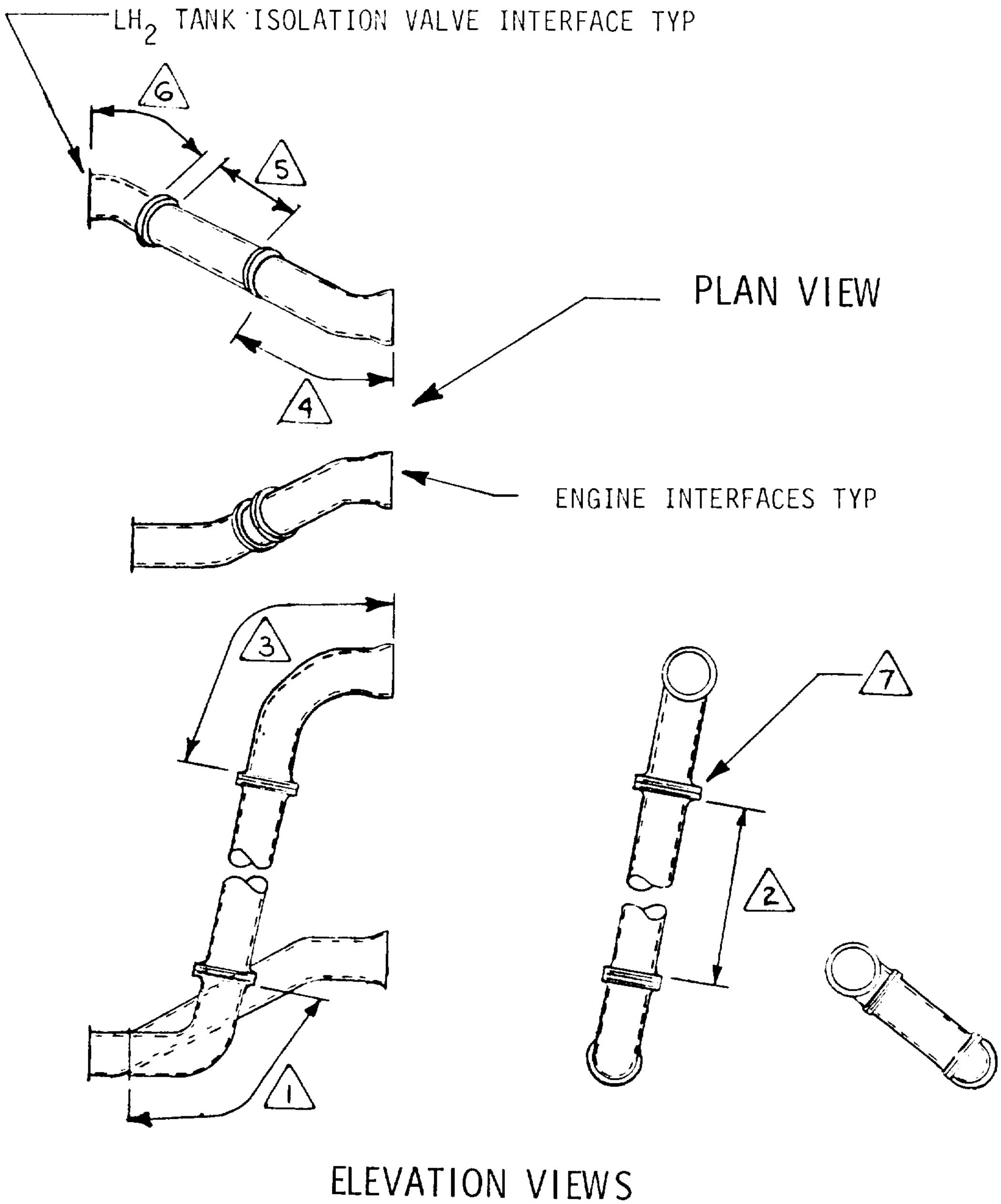


Figure B-12. - Orbiter LH_2 Main Feedline

TABLE B-12. - ORBITER LH_2 MAIN FEEDLINE

1. 61 cm (24.0 in.) long, 30 cm (12.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, inside line.
   61 cm (24.0 in.) long, 36 cm (14.0 in.) dia., 0.03 cm (0.012 in.) wall stainless steel, jacket.

2. 163 cm (64.0 in.) long, 30 cm (12.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, inside line.
   163 cm (64.0 in.) long, 36 cm (14.0 in.) dia., 0.03 cm (0.012 in.) wall stainless steel, jacket.

3. 122 cm (48.0 in.) long, 30 cm (12.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, inside line.
   122 cm (48.0 in.) long, 36 cm (14.0 in.) dia., 0.03 cm (0.012 in.) wall stainless steel, jacket.

4. 81 cm (32.0 in.) long, 30 cm (12.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, inside line.
   81 cm (32.0 in.) long, 36 cm (14.0 in.) dia., 0.03 cm (0.012 in.) wall stainless steel, jacket.

5. 122 cm (48.0 in.) long, 30 cm (12.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, inside line.
   122 cm (48.0 in.) long, 36 cm (14.0 in.) dia., 0.03 cm (0.012 in.) wall stainless steel, jacket.

6. 61 cm (24.0 in.) long, 30 cm (12.0 in.) dia., 0.13 cm (0.050 in.) wall stainless steel, inside line.
   61 cm (24.0 in.) long, 36 cm (14.0 in.) dia., 0.03 cm (0.012 in.) wall stainless steel, jacket.

7. 4 each, 36 cm (14.0 in.) dia., outside, 30 cm (12.0 in.) dia. inside jacketed bellows.

APPENDIX C

STRUCTURAL ANALYSIS

APPENDIX C

STRUCTURAL ANALYSIS

The purpose of the analysis was to develop the techniques required to predict the structural performance of the metal lined glass-fiber overwrapped, composite tubes and to provide criteria for the feedline designs.

This analysis effort was primarily concerned with the structural characteristics of the large diameter composite tubes for application in the booster and orbiter main engine propellant feed systems. The analyses performed assumed that the tubes were loaded in both the hoop and axial direction as is the case without sliding joints or bellows in the system. This results in a conservative analysis since most systems include components designed to carry the axial loads. This approach facilitates testing since no expansion devices are included. The analysis performed and the results obtained are presented in the following paragraphs.

Structural Analysis and Weight Optimization. - A structural analysis and weight optimization study was performed for all Space Shuttle candidate lines except the auxiliary power units exhaust ducts. The operating temperature of these ducts is beyond the capability of the glass-fiber and resin system planned for use on the other candidate lines. Further research will be necessary to determine if a high temperature system is available or can be developed.

This analytical model considered only the internal working pressure and thermal contraction of the line at operating temperatures. The stress analysis assumed that there is no stress in the liner or overwrap at room temperature, when the fabrication of the composite line is completed. Since the liner and overwrap materials have a different coefficient of thermal contraction, a gap will exist between the metal liner and the overwrap when the composite line is cooled to cryogenic temperature. When determining this gap for vacuum jacketed or insulated lines, the operating temperature for the liner and the overwrap will be the same as the propellant temperature. For uninsulated lines, the temperature of the liner will be the same as the propellant and the temperature of the overwrap will be at a point between the environmental temperature and the propellant temperature.

The first steps in the analytical process were to calculate the gap between the liner and the overwrap at working temperature and to determine the stress required in the liner to close this gap (i.e., bring the liner into contact with the overwrap). If this stress is equal to or greater than the maximum allowable liner stress, the liner material would be unsatisfactory except for the case where the nominal thickness liner would carry all the pressure load without exceeding the maximum allowable stress. In this event, the gap would not be closed and the overwrap would only help to absorb handling loads. If the stress required to close the gap is less than the maximum allowable liner stress, the hoop load may be transferred to the overwrap until the maximum allowable liner stress is obtained in the axial direction. This axial stress was determined by applying a 90% weld efficiency and a 1.1 safety factor to the liner material yield stress. Using this allowable axial stress, the Hencky/Von Mises[11] equation for combined stress was solved to determine the allowable hoop stress. This stress will usually result in a burst pressure of at least 200% of operating pressure but it should be verified by a simple manual calculation if the 200% is a requirement.

A minimum liner thickness consistant with the working pressure and the axial strain was then calculated and the overwrap thickness necessary to support the allowable hoop stress was determined. The computer program was then re-interated increasing the liner thickness in increments and decreasing the overwrap thickness until an optimum weight for the composite line was determined.

Combined Stress Analysis. - The data review search for feedline loads other than those imposed by internal pressure, vibration and thermal contraction was unsuccessful. No bending or torsional loading criteria for the feedlines was developed in the Phase B contract studies which formed the baseline for this contract. A review of several existing feedline specifications for the Saturn vehicle failed to provide any additional data[12]. These lines contain bellows to absorb the bending and torsional loads and the only loading criteria is from the line to adjacent equipment, i.e., interface maximum loadings. Therefore, as for the all-metal lines, bellows will be utilized to restrict the loading in the tubes to the allowable stress levels.

Following the weight optimization structural analysis performed using the WEATOPT computer program, each feedline section was analyzed to determine its capability to withstand combined stresses even though the actual stresses should be low with bellows in the system. These stresses include bending, torsion, and compressive buckling as mentioned above, as well as the internal pressure and thermal stresses considered in the WEATOPT program. The approach to the combined stress analysis was as follows:

- The hoop stresses in the liner and the overwrap were determined using the WEATOPT program.

- The longitudinal stresses considered were the algebraic sum of those due to internal pressure, thermal expansion characteristics and bending stresses.

- The torsional analysis determined the allowable torque that can be applied to the optimum feedline section.

The WEATOPT program provided the optimum feedline sections which will carry all the internal pressure stresses and thermal expansion stresses which result in axial tensile stresses in the liner. The output of this program provides the optimum liner thickness, overwrap thickness, actual liner hoop

(S_{1h}) and axial stresses (S_{1a}), the maximum allowable liner axial stress (S_{1am}), and the liner axial thermal tension stresses (S_{1t}). The program analyses the thermal characteristics of the overwrap and liner in the axial direction and utilizes those stresses which result in tension in the liner. If these stresses resulted in compression the S_{1t} was considered to be zero. If the output of S_{1t} from the WEATOPT program was zero, the feedline section was analyzed to insure that critical buckling stresses were not exceeded due to thermally induced compressive loads. The liner stresses were calculated as follows:

$$S_{LT} = \frac{\Delta T_o \alpha_o - \Delta T_1 \alpha_1}{\frac{A_1}{E_o A_o} + \frac{1}{E_1}}$$

where

S_{1t} = Axial liner stress due to thermal expansion (positive indicates tension and negative indicates compression), in N/sq cm

ΔT_o = Change in overwrap temperature, (negative if temperature is lowered and positive if temperature rises), in K

ΔT_1 = Change in liner temperature, (negative if temperature is lowered and positive if temperature rises), in K

α_o = Overwrap coefficient of thermal expansion in axial direction in cm/cm K

α_1 = Liner coefficient of thermal expansion, in cm/cm K

A_1 = Cross-sectional liner area, in cm^2

A_o = Cross-sectional overwrap area, in cm^2

E_o = Overwrap modulus of elasticity, in N/sq cm

E_1 = Liner modulus of elasticity, in N/sq cm.

The unpressurized compressive stress, S_{1t}, as calculated was then compared to the critical buckling stress, S_{bc}, to ensure that liner buckling would not occur when the unpressurized feedline is cooled down to working temperature, using

$$S_{bc} = 0.3\, E_1 \frac{t_1}{r}$$

where

S_{bc} = Critical compressive buckling stress in axial direction, in N/sq cm

t_1 = Liner thickness, in cm

r = Liner radius (nominal), in cm

E_1 = Liner modulus of elasticity, in N/sq cm.

The stresses due to internal pressure and thermal expansion were then added algebraically to determine the resulting axial stresses in the liner at operating conditions. This resultant axial stress was then subtracted from the maximum allowable axial stress determined from the WEATOPT program to determine the amount of bending stresses that can be tolerated in the liner. The maximum allowable bending moment or side load for a given feedline length was then determined.

Since $S_{b1} = S_{1am} - (S_{1a} + S_{1t})$

and $S_{b1} = E_1 \epsilon_1$ and $S_{bo} = E_o \epsilon_o$

where

S_{b1} = Bending stress in liner, in N/sq cm

ϵ_1 = Strain in liner due to bending, in cm/cm

ϵ_o = Strain in overwrap due to bending, in cm/cm

S_{bo} = Bending stress in the overwrap, in N/sq cm

and since the overwrap and liner must deflect together,

$$\epsilon_1 = \epsilon_o = \epsilon_c$$

where ϵ_c = strain in the composite feedline

the bending stress in the composite feedline is

$$S_b = \frac{My}{I} = E_c \epsilon_c$$

where

M = Bending moment, in N-cm

y = Distance from neutral axis to extreme fiber, in cm

I = Cross section moment of inertia, in cm^4

E_c = Composite modulus of elasticity, in N/sq cm.

E_c was calculated as follows:

$$E_c = \frac{t_o}{t_o + t_1} (E_o) + \frac{t_1}{t_o + t_1} (E_1)$$

where

t_o = Thickness of overwrap, in cm, and

t_1 = Thickness of liner, in cm.

Knowing the allowable bending stress in the liner (S_{b1}), the strain (ϵ_c) can be calculated, and then the composite bending stress (S_b) can be calculated from $S_b = E_c \epsilon_c$. The bending moment (M) was calculated as,

$$M = \frac{S_b I}{y}$$

and for a given feedline section length (L) the allowable side load force (F) was determined as $F = \frac{M}{L}$ where the units of M are best presented as Newton-meters.

The above analysis determined the bending loads that the feedline can withstand without exceeding the liner stresses allowable in the axial direction, i.e.,

$$S_{1am} = S_{1a} + S_{1t} + S_{b1}.$$

The maximum allowable torque that can be applied to the feedline was determined the same as in the previous program (NAS3-12047) as

$$T = \frac{2 \pi r^2 t S_{st}}{100}$$

where

T = Allowable torque, in N-m

r = Liner radius or overwrap radius, in cm

t = Liner thickness or overwrap thickness, in cm

S_{st} = Shear stress due to torsion, in N/sq cm,

and S_{st} was calculated based on the $\frac{L}{r}$ values for the feedline section being considered using formulas from Roark page 353 case 28[13]

The results of this combined stress analysis are shown in Table C-1. They indicate that all feedlines analyzed are capable of sustaining at least moderate external loads. Because no external load carrying capability is specifically designed for in Saturn, it is concluded that the composite lines will be satisfactory in the Space Shuttle application with respect to external loads.

During the test program the feedlines were subjected to bending loads of 25% of allowable and torsion loads of twice to eight times the load allowed by the liner only. These test levels were chosen to assure that the lines are capable of withstanding the loads transmitted to them in a Space Shuttle application.

Axial Direction Structural Analysis. - An analysis was performed to determine the effects, if any, of the restraints to the movements of the overwrap which were created by the line configuration in the axial direction. The analysis covers axial loadings only. The importance of this analysis is exemplified by the main engine LOX line which was to be fabricated in four liner sections joined together with a series of hoop rings and resistance welds. A detailed lay out of the LOX tube is shown in Figure C-1.

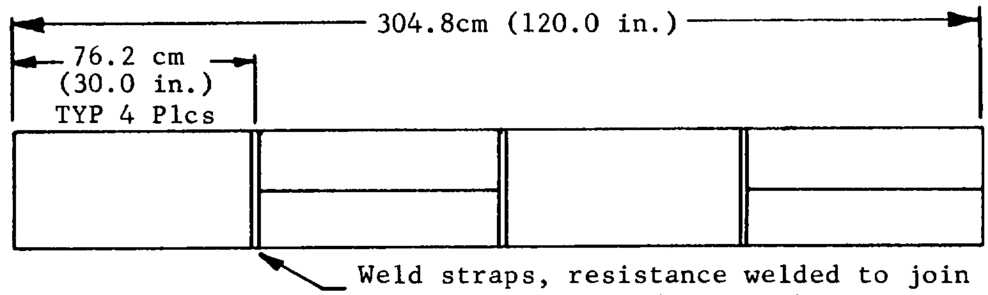
The following conditions were analyzed for stresses in the overwrap and/or the liner as applicable:

- o During overwrap
- o During curing of the composite
- o During normal pressurization
- o During cryogenic cooling
- o During pressurization while cold
- o During warmup
- o During burst

Condition during winding of the overwrap on the liner: The liner was to be internally pressurized to 28 N/sq cm (40 psi) during winding. The stress in the liner (axially) at this pressure can be expressed as

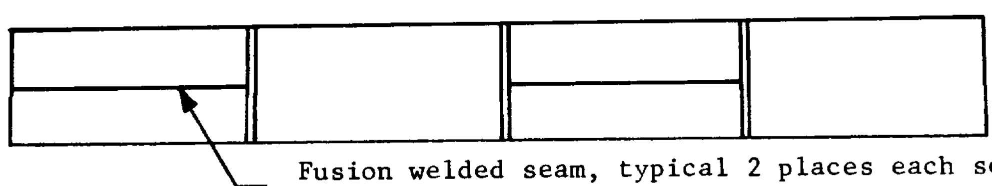
$$S = \frac{pr}{2t} = \frac{28 \times 19}{2 \times 0.028} = 9{,}500 \text{ N/sq cm } (13{,}778 \text{ psi})$$

A detail layout of the LOX tube is shown in Figure C-1.



Weld straps, resistance welded to join liner sections. 1.9 cm (0.75 in.) wide, 0.08 cm (0.030 in.) thick, entire circumference. Typical 3 weld straps.

TOP VIEW



Fusion welded seam, typical 2 places each section 3.14 radians (180 degrees) apart. Seams are staggered section to section. Fusion welded seams made prior to resistance welding sections together.

SIDE VIEW

Figure C-1. - Layout of LOX Tube Liner Showing Rings

TABLE C-1. - ALLOWABLES BENDING AND TORQUE STRESSES (INTERNATIONAL UNITS)

Description	Section Code	Material	Allowable Bending Tension Failure N-cm	Allowable Bending Buckling Failure N-cm	Allowable Torque Liner Only N-cm	Allowable Torque Liner and Overwrap N-cm
Booster Main Engine LOX Feed line	3A	Inconel	27,700	16,800	230	2860
	3A	21-6-9	23,700	16,300	230	2790
	4A	Inconel	16,500	18,700	230	2280
	4B	Inconel	4,600	21,300	310	2630
	4C	Inconel	12,700	25,100	460	3510
	4D	Inconel	19,800	29,100	640	3000
	5	Inconel	35,400	33,400	850	4240
	5	21-6-9	31,600	33,200	890	4180
Booster Main Engine LOX Manifold	6A	Inconel	24,900	45,600	3100	11860
	8A	Inconel	3,000	5,600	50	720
Booster Main LOX Feed Duct	4A	Inconel	2,220	11,400	300	2600
	1	Inconel	12,130	19,300	660	3990
Booster Main LH_2 Feed Duct	1	Inconel	8,930	5,600	40	1570
	14 & 15	Inconel	11,620	7,080	30	1360
Orbiter Main LOX Feedline	1A	Inconel	23,500	12,500	100	1250
	8A	Inconel	12,050	14,800	340	3690
Orbiter Main LH_2 Feedline	2	Inconel	14,400	5,600	30	1100

TABLE C-1. - ALLOWABLE BENDING AND TORQUE STRESSES (CONVENTIONAL UNITS)

DESCRIPTION	Section Code	Material	ALLOWABLE BENDING Tension Failure FT-LB	ALLOWABLE BENDING Buckling Failure FT-LB	ALLOWABLE TORQUE Liner Only FT-LB	ALLOWABLE TORQUE Liner and Overwrap FT-LB
Booster Main Engine LOX Feed line	3A	Inconel	20,400	12,400	170	2110
	3A	21-6-9	17,500	12,000	170	2060
	4A	Inconel	12,200	13,800	170	1680
	4B	Inconel	3,400	15,700	230	1940
	4C	Inconel	9,400	18,500	340	2590
	4D	Inconel	14,600	21,500	470	2210
	5	Inconel	26,100	24,600	630	3130
	5	21-6-9	23,300	24,500	660	3080
Booster Main Engine LOX Manifold	6A	Inconel	18,400	33,600	2300	8750
	8A	Inconel	2,000	4,140	37	530
Booster Main LOX Feed Duct	4A	Inconel	1,640	8,430	220	1920
	1	Inconel	8,950	14,200	490	2940
Booster Main LH_2 Feed Duct	1	Inconel	6,590	4,140	29	1160
	14 & 15	Inconel	8,570	5,170	25	1000
Orbiter Main LOX Feedline	1A	Inconel	17,300	9,240	70	920
	8A	Inconel	8,890	10,900	253	2720
Orbiter Main LH_2 Feedline	2	Inconel	10,600	4,140	20	810

The deflection (δ) represented by this stress can be expressed as:

$$\delta = \epsilon L$$

where ϵ = strain, in micro cm/cm

and L = tube or section length, in cm.

Accounting for Poisson's effect the axial strain will be expressed as:

$$\epsilon = \frac{\frac{pr}{2t} - .3\,\frac{pr}{t}}{E} = .2\,\frac{pr}{tE}$$

Substituting and solving, the strain for the tube will be:

$$\epsilon = .2\,\frac{(28)\ (19)}{0.028 \times 20{,}200{,}000} = 0.0002 \text{ cm/cm}$$

and the deflection will be
δ = 0.0002 x 305 = 0.0610 cm (0.0240 in.) or δ = 0.0002 x 76 = 0.0152 cm (0.0059 in.) for the total length and a single segment respectively. When the composite is uncured it will not present any axial restrictions, but this liner strain will eventually be relieved when the tube is vented after curing. In order to assure no stress risers the transition onto each of the seams will need to be smoothed by filling the hump or ring edges with composite.

Condition during curing of the overwrap: As the composite cures it may attach to the knurls in the seams of the hoop rings. These dimples or knurls are formed when the resistance welding is accomplished. They are fairly deep and serve the same gripping function as a knurl although not as efficiently. When the pressure is vented this will result in compression in the composite and a residual tension in the liner which must be considered during subsequent pressure operations. This will also result in a tensile load (axially) in the overwrap during any pressurization greater than the cure pressure of 28 N/sq cm (40 psi).

For stresses during venting after cure, assuming an E of 1.1×10^6 N/sq cm (1.6×10^6 psi), a thickness of 0.05 cm (0.02 in.) and a diameter of 38 cm (15 in.) for the cured overwrap and an E of 20.2×10^6 N/sq cm (29×10^6 psi) t = 0.028 cm (0.011 in.) and a diameter of 38 cm (15 in.) for the liner; the, stresses when the pressure is vented and the overwrap goes into compression and the liner in tension, can be calculated as:

$S_o = E_o \epsilon_o$; $S_L = E_L \epsilon_L$

$$\text{or} \quad \frac{B_o}{A_o} = E_o \epsilon_o \quad ; \quad \frac{B_L}{A_L} = E_L \epsilon_L$$

where B = Force, in N/sq cm

A = Area of the cross section, in sq cm

E = Modulus of elasticity, in N/sq cm

ϵ = Strain, in cm/cm

and S = Stress in N/sq cm.

This analysis assumes pinned ends. Next, equating $B_o = B_L$,

$$E_o \epsilon_o A_o = E_L \epsilon_L A_L$$

$$\text{of } \epsilon_L = \frac{E_o \epsilon_o A_o}{E_L A_L} = \frac{1.1 \times 10^6 \times 38 \times \pi \times 0.050}{20.2 \times 10^6 \times 38 \times \pi \times 0.028} = 0.1003 \ \epsilon_o$$

This states simply that the relaxing strain in the liner will be 10% as much as the relaxing strain in the overwrap, the overwrap then is the weaker member. With a total strain of 0.000188 cm/cm, the liner will retain 10/11 x 0.000188 or 0.013 cm (0.005 in.) per bay and the liner will be forced into compression at a unit ϵ = 0.000017 cm/cm or 0.0013 cm (0.0005 in.) per bay. For these strains the resultant stresses are found to be:

$S_L = E_L \epsilon_L$ = 343 N/sq cm (498 psi) tensile, and

$S_o = E_o \epsilon_o$ = 187 N/sq cm (271 psi) compressive.

Another approach to this portion of the analysis, based upon the equations in reference (1) gives the same results.

The liner tensile stress is minor and will not be a problem at this point in time. For the composite, compressive buckling allowables are found to be $S' = 0.3\ E \frac{t}{r}$ = 883 N/sq cm (1280 psi). This is condition M from Roark (13) with a length of 76cm (30 in.) which is 45 times $1.7\sqrt{7.5 \times 0.20}$. This gives an allowable considerably higher than the expected load.

During normal pressurization: Assuming the composite is pinned to the section, it will be loaded concurrent with the liner. With an operating pressure of 259 N/sq cm (375 psi), the liner stress (with no overwrap assistance) would be

$$S = \frac{pr}{2t} = \frac{(259)\ (19)}{2 \times 0.028} = 87{,}875 \text{ N/sq cm } (127{,}447 \text{ psi})$$

which is well below the allowable working stress of 115,800 N/sq cm (165,000 psi) for the Inconel 718, heat treated material.

The composite will contain tension as a function of the relation shown below as derived earlier where

$$E_o \epsilon_o A_o = E_L \epsilon_L A_L \quad \text{or from above} \quad \epsilon_L = .1\ \epsilon_o.$$

Now for a total $\epsilon = \frac{S}{E} = \frac{87{,}900}{20{,}200{,}000} = 0.0044$ cm/cm

of which 1/11 is in the liner = 0.0004 cm/cm

and 10/11 is in the composite = 0.004 cm/cm.

The composite stress will be

$S_o = E_o \epsilon_o = 1{,}100{,}000 \times 0.004 = 4{,}400$ N/sq cm (6,381 psi) tensile,

and the liner stress will be

$S_L = E_L \epsilon_L = 20{,}200{,}000 \text{ X } .004 = 8080$ N/sq cm (11,716 psi) less than without any overwrap assistance or a net of 87,900 - 8080 = 79,820 N/sq cm (115,739 psi). These stresses are very acceptable for both the liner and overwrap. The overwrap style 1557 axially oriented cloth has a tensile strength of 51,712 N/sq cm (75,000 psi) and it forms 1/5 of the total area for an average strength of 10,342 N/sq cm (15,000 psi) with no allowable for any resin strength.

During cooling to 78 K (-320^{o}F): The worst case would be childown where the liner would reach the operating temperature of 78 K (-320^{o}F) while the composite remained at ambient temperature. This is very unlikely in a line of this diameter and inherent slow fill. Looking at one bay, 76 cm (30 in.) long, and assuming pinned ends between the overwrap and liner, thermal stresses can be calculated. First the change in liner length (ΔL_L) if it were unrestrained would be

$$\Delta L_L = L \times \alpha \times \Delta T$$

$$= 76 \text{ X } 1.02 \times 10^{-5} \times 217$$

$$= 0.168 \text{ cm } (0.066 \text{ in.}).$$

This total deflection will be shared by the liner and the overwrap as a ratio of their stiffnesses. Reviewing the strain ratios, as developed above, 1/11 x 0.168 cm will be tensile δ in the liner, or 0.015 cm/76 cm (0.006 in./30 in.) or 0.0002 cm/cm and 10/11 x 0.168 will be compressive δ in the overwrap or 0.153 cm/76 cm (0.060 in/30 in.) or 0.002 cm/cm. This will result in a composite compressive stress of

$S_o = E_o \epsilon_o = 1{,}100{,}000 \times .002 = 2{,}200$ N/sq cm (3,190 psi), compressive. With an allowable per Roark of only 883 N/sq cm (1280 psi) (from above), this will result in an excessive load. The liner tensile stress will be

$S_L = E_L \epsilon_L = 20{,}200{,}000 \times .0002 = 4040$ N/sq cm (5,859 psi), tensile.

This stress level, when added to the internal pressure stress is still in the acceptable range.

Next, an allowable ΔT across the tube section so as not to exceed a 883 N/sq cm (1280 psi) compressive stress can be determined. This can be shown to be a ratio where the allowable strain is

$$\epsilon_o = \frac{883}{2200} \times 0.002 = 0.0008 \text{ cm/cm}$$

and the total deflection for the bay is

$$\delta = 0.0008 \times 76 = 0.061 \text{ cm}/76 \text{ cm } (0.024 \text{ in.}/30 \text{ in.}).$$

Given an average coefficient of thermal expansion of

$$\alpha_o = 1.02 \times 10^{-5} \text{ cm/cm/K}$$

The allowable ΔT between the materials can be determined as

$$\Delta T = \frac{\Delta L_L}{L\,\alpha} = \frac{0.061}{76\,(1.02 \times 10^{-5})} = 79 \text{ K } (140^{\circ}\text{F}).$$

During pressurization while cold: The stresses due to pressurization while the tube is cold will be very similar to the stresses during pressurization at ambient temperature and no problems were encountered in that condition.

During warmup: In this case the liner may warm up quicker than the overwrap resulting in a tensile stress in the overwrap and a compressive stress in the liner. The tensile stress in the overwrap bay will not exceed the 2200 N/sq cm (3,200 psi) maximum during cooldown and, therefore, will present no problems. Looking at the liner in compression, assuming a temperature differential between the overwrap and the liner of 55 K (100 $^{\circ}$F):

$$\Delta L_L = L \times \delta \times \Delta T$$

$$= 76 \times 1.02 \times 10^{-5} \times 55$$

$$= 0.043 \text{ cm}/76 \text{ cm } (0.017 \text{ in}/30 \text{ in.}), \text{ total deflection.}$$

By utilizing the strain ratios, 1/11 x 0.043 will be compression in the liner or 0.0039 cm (0.0015 in.)/76 cm (30 in.) which will be a strain of 0.00005 cm/cm. This will be a compressive axial strain which is undesirable. An offsetting internal pressure is an easy solution and can be calculated as

$$S = \frac{pr}{2t} = E\,\epsilon$$

$$p = E\,\epsilon\ 2t/r$$

$$= 20{,}200{,}000 \times 0.00005 \times 2 \times 0.028/19$$

$$= 3 \text{ N/sq cm } (4.35 \text{ psi}).$$

Therefore, during thermal cycle warmups and all other warmups a pressure of 6.9 N/sq cm (10 psi) in the tube will more than offset any compressive forces. The overwrap would have a tensile deflection of 10/11 x 0.043 = 0.039 cm which equates to a strain of 0.0005 cm/cm.

In the application of this concept to a launch vehicle a positive pressure blanket may be undesirable. However, under normal warmup the glass temperature will always be warmer than the metal and no blanket will be required. If warm gas is purged through the line, warming the liner more rapidly, a positive pressure will automatically exist.

During burst: This will be an ambient temperature test. The failure mode should be at one end of the tube with a burst pressure of

$$P = \frac{S\ 2t}{r} = \frac{131{,}000 \times 2 \times 0.028}{19} = 386 \text{ N/sq cm } (560 \text{ psi}).$$

This would equate to

$$P = \frac{S\ 2t}{r} = \frac{165{,}000 \times 2 \times 0.028}{19} = 486 \text{ N/sq cm (705 psi)}$$

at LN_2 temperature with the increase in ultimate strength. First, looking at 1 bay and the tensile stress in the overwrap in that bay, and equating

$$\epsilon_L = \epsilon_o, \quad \frac{P_1\ r}{2t_1\ E_1} = \frac{P_o\ r}{2t_o\ E_o} \quad \text{and}$$

$$P_o = \frac{P_1 t_o E_o}{t_1 E_1},$$

by combining and simplifying, assuming $r_o = r_1$. Then

$$P_o = \frac{0.051 \times 1{,}100{,}000}{0.020 \times 20{,}200{,}000}\ P_1 = 0.1\ P_1.$$

Then the P_o = 1/11 x 386 or 35 N/sq cm (51 psi). The overwrap stress in the longitudinal cloth only can be defined by

$$S = \frac{Pr}{2t} = \frac{35 \times 19}{2 \times 0.010} = 33{,}250 \text{ N/sq cm (48,223 psi), with a tensile}$$

allowable of 51,800 N/sq cm (75,126 psi).

Conclusions: As a result of this analysis the following conclusions can be stated:

- o There are no major problems created by the addition of the hoop rings;
- o The transition onto each of the seams or rings must be smoothed by filling the sharp dropoff from the ring to the liner with composite;
- o The temperature differential between the liner and glass thermocouple should not exceed 50 K (90^{o}F). This may require additional instrumentation during any additional development or flight hardware qualification program;

- During thermal cycle warmups and all other warmups, including eventual post-flight conditions a nominal 7 N/sq cm (10 psi) in the tube will preclude any compressive loading on the liner. If the tube warms up from the outside, this will be unnecessary.

- The addition of the hoop rings will provide a substantial rigidity for handling purposes for only a slight increase in weight. For production runs, a cost tradeoff should be accomplished comparing the additional welds to additional tooling to make 3 to 6 meter (10 to 20 ft.) long pieces without splices.

APPENDIX D

THERMAL ANALYSIS

APPENDIX D

APPENDIX D (Continued)

THERMAL ANALYSIS

The purpose of this analysis was to develop the analytical techniques required to predict the thermal performance of the metal-lined glass-fiber composite feedlines and to establish criteria for the feedline design.

The ultimate objective of this program was to increase the payload capability of the Space Shuttle Vehicle. This objective can be accomplished by reducing the weight of the propulsion system components and by limiting the propellant lost due to boiloff and overboard bleed during line cooldowns. The analysis activity during the program was, therefore, directed at the following items, as pertaining to the OMS or ACPS system:

- Propellant expended in cooling lines prior to engine restarts;
- Boiloff of propellants due to lateral and radial heat input and conduction along the feedline;
- Flange and/or connector design and weights;
- Basic feedline structural weight;
- Weight of insulation necessary on or in the feedline;
- Weight of a vacuum jacket;
- Effect of the number of feedline refills required for system restarts;
- Weight of the pressurization system as a function of pressure drop;
- Various planned flowrates.

<u>OMS LOX Steady-State Heat Input</u>. - This analysis was performed on the flight configuration of the OMS LOX feedline for each of the following conditions.

- Bare line - all-metal - - emissivity (e) reflective;
- Bare line - composite - - emissivity (e) not reflective;
- Insulated line - all-metal;
- Insulated line - composite;
- Vacuum jacketed line - composite;

- o Vacuum jacketed line - all-metal;
- o Insulated and vacuum jacketed line - all-metal;
- o Insulated and vacuum jacketed line - composite.

The analysis was also performed on the test configuration of the OMS LOX feedline for the following conditions:

- o Bare line - composite - - emissivity (e) not reflective; and
- o Insulated line - composite - - emissivity (e) reflective thru insulation but unpolished overwrap on feedline.

The mass of the engine at the feedline outlet and the mass of a flow initiating valve in the feedline were included in the analysis for each condition.

The feedline system analyzed was the flight configured system of the OMS LOX feedline. This feedline has a length of 1130 cm (446 in.) with a diameter of 6.7 cm (2.6 in.) and a length of 280 cm (110 in.) with a diameter of 5.5 cm (2.1 in.). The smaller diameter line is connected to the engine. A dry section of feedline is provided next to the engine to give thermal resistance. The mission duration was assumed to be 200 hours with a nominal environmental temperature of 294 K (70°F) which intercepts the space shuttle studies, where the hot case was 317 K (110°F) and the cold case was 278 K (40°F). Liquid oxygen propellant temperature was set at 91 K (-296°F) and the heat of vaporization as 213 joules/g (91.7 Btu/lb). A summary of the propellant boiloff is shown in Table D-1.

Uninsulated feedline: The heat transfer to the uninsulated feedline was considered to be radiation from the shuttle environment and conduction and radiation from the dry feedline end.

The radiation heat transfer to the uninsulated all-metal line from the shuttle environment was determined from the expression:

$$Q = e_f A_f \sigma (T_E^4 - T_f^4)$$

where

Q = Total radiation heat transfer, watts

A_f = Surface area of feedline, in m^2

TABLE 3. - SUMMARY OF PROPELLANT LOSSES DUE TO BOILOFF FOR OMS LOX FEEDLINE

Configuration	Feed-line Type	Thermal System	Insulation Loss kg	Insulation Loss lb	Feedline End Loss † kg	Feedline End Loss † lb	Vacuum Jacket Support Loss kg	Vacuum Jacket Support Loss lb	Insulation Joint Loss kg	Insulation Joint Loss lb	Total kg	Total lb
LOX OMS Flight System	All-metal	Bare Line	e_s = .28		L/D = 3							
			1135	2500	42	93					1179	2593
		Insulated Line			L/D = 6							
			52	115	14	30			2	5	68	150
		Vacuum Jacket No Insulation	e_s = .026		*L/D = 6							
			99	218	29	65	106	234	.		283	623
		Vacuum Jacket Insulation			L/D = 6							
			63	139	14	30	106	234	2	5	234	514
	Composite	Bare Line	e_s = .85		L/D = 3							
			2028	4468	30	67					2061	4535
		One Layer MLI	e_s = .026		L/D = 6							
			93	205	15	33					108	238
		Insulated Line			L/D = 6							
			52	115	5	12			2	5	60	132
		Vacuum Jacket No Insulation	e_s = .026		*L/D = 6							
			93	205	15	33	106	234			263	578
		Vacuum Jacket Insulation			L/D = 6							
			63	139	5	12	106	234	2	5	225	496

NOTE: e_s = Surface Emissivity of Feedline

L/D = Length to Diameter Ratio of Feedline End, Dry Section

* = Boiloff Includes Wet Section Equal to Dry Section

† = Feedline End Loss Includes Two Engines

T_E = Environmental temperature, in K

T_f = Feedline temperature, in K

e_f = Emissivity of feedline surface

σ = Stefan-Boltzmann constant, in $W/(m^2)(K^4)$.

This equation is valid when the feedline is small compared with the shuttle compartments. An emissivity of 0.28 was assumed as a representative value for the uninsulated all-metal line and is characteristic of as-received stainless steel. This value was chosen since the feedline is unprotected from the environment. The boiloff of propellant for this line is a strong function of the surface emissivity as shown in Figure D-1.

Thermal analyzer computer programs were used to calculate the heat transfer from the feedline end. For this analysis, the environmental temperature and the engine temperature were assumed to be the same. The feedline end emissivities were set at 1 and values of the heat transfer rate were determined for hot, cold and nominal cases. These values are plotted in Figure D-2 as a function of the length-to-diameter ratio of the feedline end dry section. The wall thickness selected for the all-metal feedline was 0.041 cm (0.016 in.) which is considerably thinner than would actually be used. The loss may be twice this high for practical feedline thicknesses. This data indicates, at a L/D of 3, the heat transfer rate has decreased significantly. This L/D was used to calculate the boiloff for the uninsulated line. A plot of a typical temperature distribution in this feedline end is shown in Figure D-3.

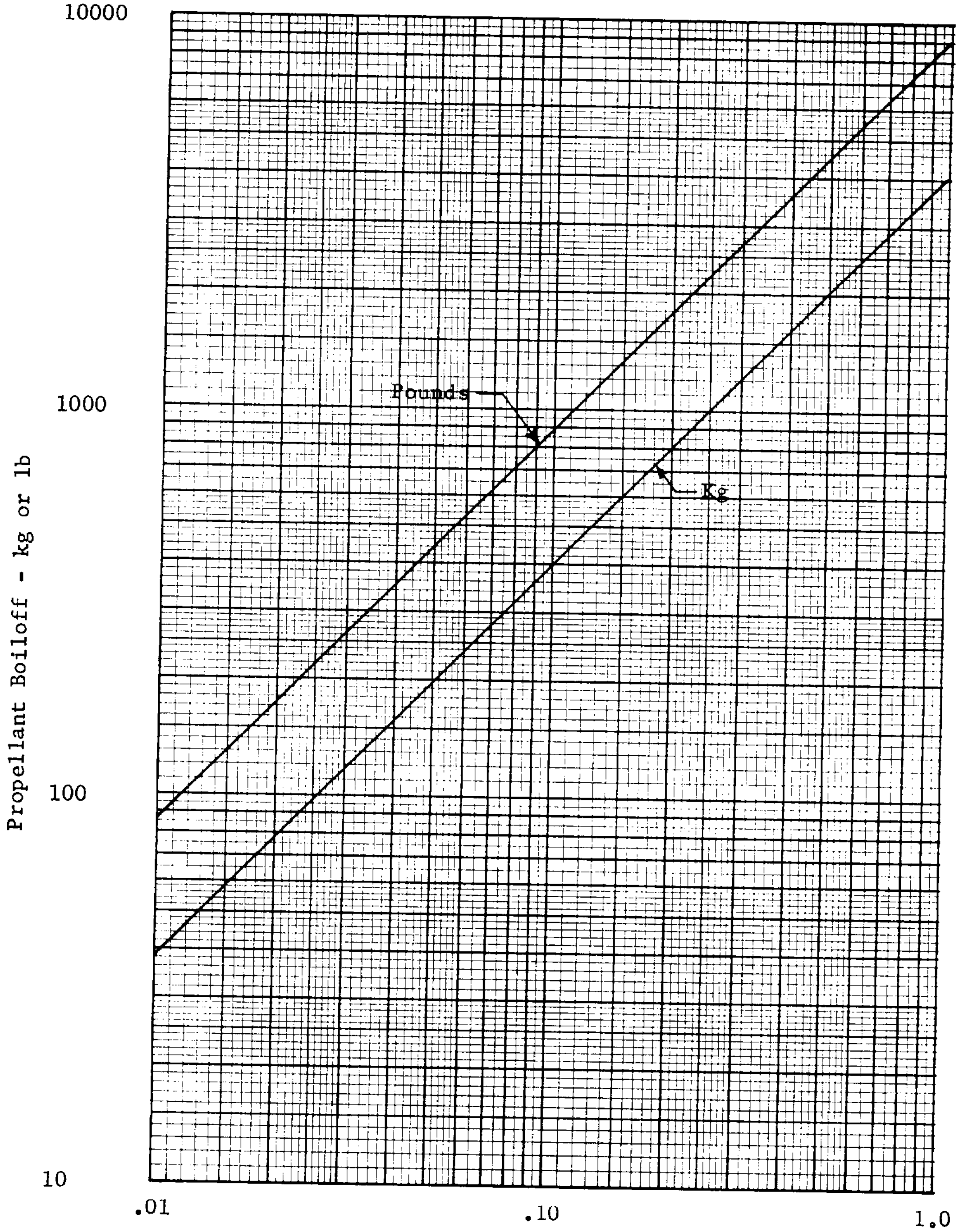
For the composite feedline, the gap between the overwrap and the metal liner offers some resistance to the heat flow. Consequently, this analysis assumes 50 percent of the area of the composite line to have a gap. The remaining 50 percent is assumed to have the metal liner in good contact with the overwrap. The heat transfer for the area in contact can be calculated similar to the uninsulated all-metal feedline. The heat transfer to the composite line where the gap exists requires a different type of analysis. By taking a heat balance as follows:

$$e_o A_f \left(T_E^4 - T_o^4\right)\sigma = \left(\frac{1}{\frac{1}{e_o} + \frac{1}{e_L} - 1}\right)\sigma A_f \left(T_o^4 - T_L^4\right)$$

where

A_f = Feedline surface area, in m^2

T_E = Environmental temperature, in K



Mission Time - 200 Hr
Environmental Temperature - 294 K (70°F)
Flight System

Figure D-1. - Surface Emissivity Effect on Liquid Oxygen Boiloff for Bare All-metal Line.

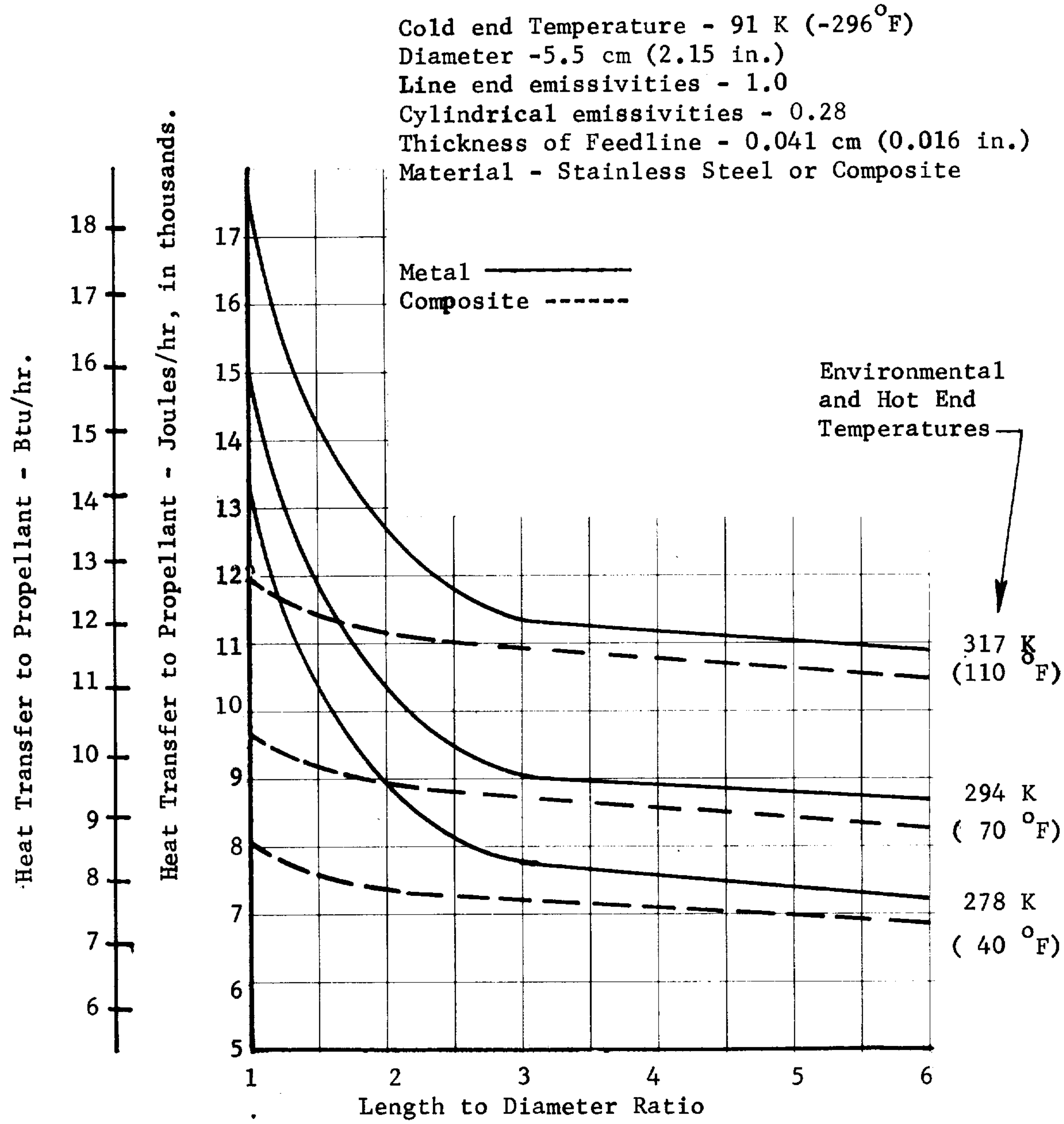


Figure D-2. - Heat Transfer to Liquid Oxygen for Uninsulsted All-Metal and Composite Feedline End Sections

Environmental Temperature 294 K (70°F)
Hot end Temperature 294 K (70°F)
Cold end Temperature 91 K (-296°F)
End Emissivity - 1.0
Cylindrical Emissivity - 0.28
Diameter - 5.5 cm (2.15 in.)
Length - 30 cm (12 in.)
Feedline thickness - 0.041 cm (0.016 in.)
Material - Stainless Steel

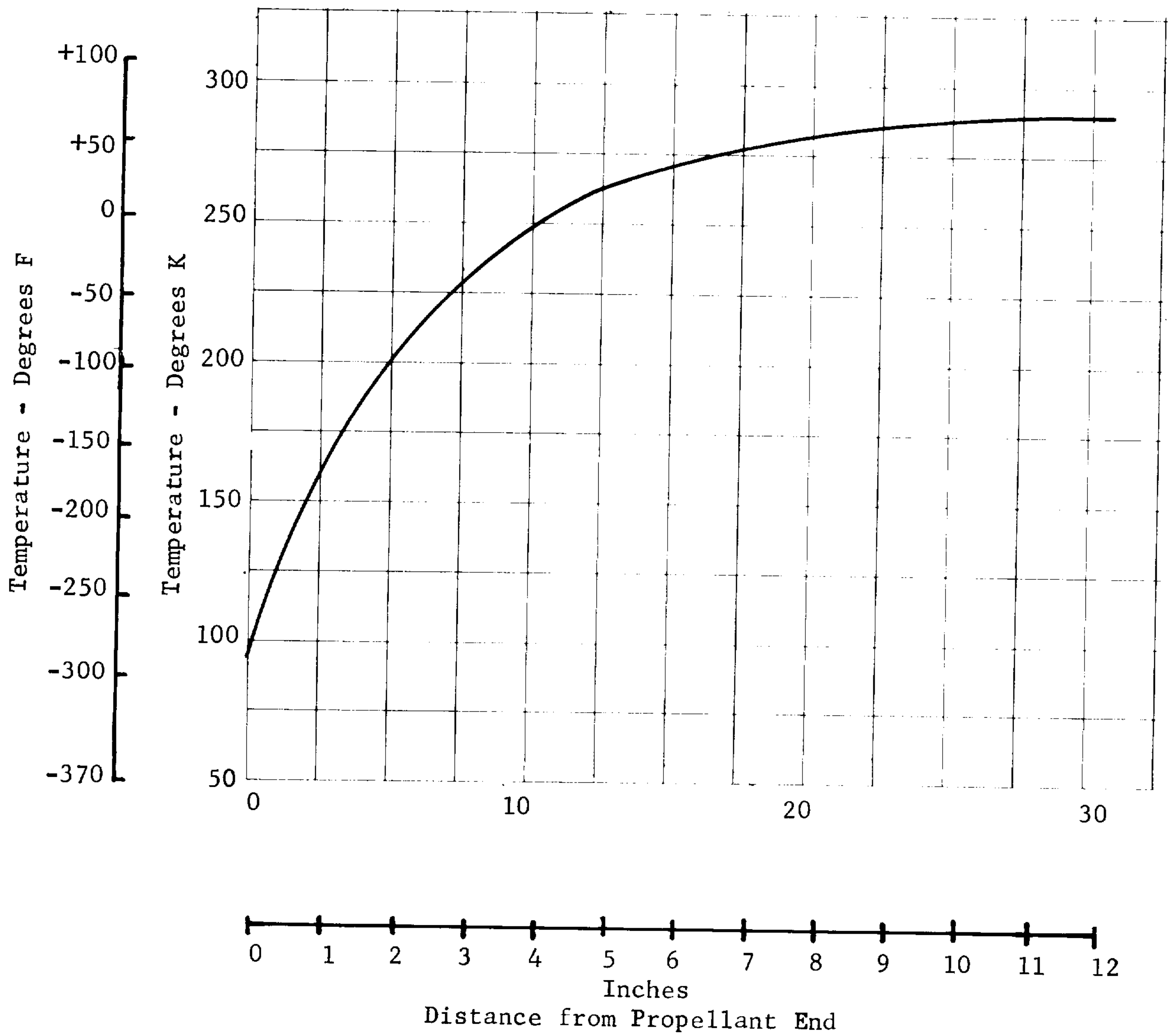


Figure D-3. - Typical Temperature Distribution for Uninsulated All-Metal Feedline End Section

T_L = Liner temperature, in K

T_o = Overwrap temperature, in K

e_o = Overwrap emissivity - 0.85

E_L = Inconel liner emissivity - 0.2

σ = Stefan-Boltzmann constant, in $W/(m^2)(K^4)$

This equation assumes the feedline is small compared with the shuttle compartments and the liner is approximately the same diameter as the overwrap but not in contact with the overwrap. Solving this expression for the overwrap temperature:

$$T_o = \left[\frac{e_o\left(\frac{1}{e_o} + \frac{1}{e_L} - 1\right) T_E^4 + T_L^4}{1 + e_o\left(\frac{1}{e_o} + \frac{1}{e_L} - 1\right)}\right]^{1/4}$$

and, as stated earlier, the heat transfer to the propellant is

$$Q = e_o A_f \sigma (T_E^4 - T_o^4).$$

The boiloff is defined as

B = 3.6 Qt/q

where

q = Heat of vaporization, in joules/gm

t = Mission time, in hours

Q = Total heat per hour, in watts, and

B = Boiloff, in kg.

The surface emissivity of the overwrap is 0.85 which causes more boiloff of propellant than the all-metal line.

The heat transfer to the propellant from the dry end section was again determined from thermal analyzer computer programs. The heat rate was plotted in Figure D-2. A L/D of 3 was used for the boiloff calculation. The Inconel liner emissivity is 0.2 and the feedline end emissivities were chosen as 1.0. The thermal conductivity of the composite feedline is plotted in Figure D-4.

Insulated feedline: The insulated feedline requires a nitrogen purge. The heat gained by the propellant is through the insulation joints, the feedline dry end section and insulation attachment points. The insulation, however, is attached to the feedline with nylon cord and the cord contributes no appreciable heat gain to the propellant. The insulation consists of alternate layers of double aluminized mylar and nylon netting and is considered to have a nominal conductivity of 9×10^{-4} Watt/m-K (5×10^{-4} Btu/ft-hr-$^{\circ}$F) and a density of 80 kg/m^3 (5 lb/ft^3) for the refurbishable Space Shuttle.

The effect of conductivity on optimum insulation thicknesses for feedline diameters of 5.5 and 6.7 cm (2.15 and 2.65 in.) and temperatures of 317 and 278 K (110 and 40°F) is shown in Figures D-5 and D-6. The boiloff per meter of feedline for a feedline diameter of 6.7 cm (2.65 in.) is shown in Figure D-7 as a function of conductivity and mission time. This figure shows the importance of low insulation conductivity for minimum boiloff.

The heat transfer to the propellant by the feedline end is shown in Figure D-8 as a function of temperature and insulated length to diameter ratio. Again a very thin all-metal line was selected for this comparison. A L/D of 6 was picked as a typical insulated dry section for the boiloff calculation. Figure D-9 shows a typical temperature distribution along the axial section of the dry end of an all-metal feedline.

The insulation was assumed to have joints every 132 cm (52 in.) and the joint coefficient was chosen as 0.073 cm^2/cm (0.0024 ft^2/ft). The joint coefficient is defined as:

$$Q = e_j \sigma A (T_h^4 - T_c^4)$$

where

$$e_j = \frac{1}{A} \sum_i C_i L_i$$

Thermal conductance of composite feedline from CFL 6300611 S/N 83, Reference 1,Page 189.

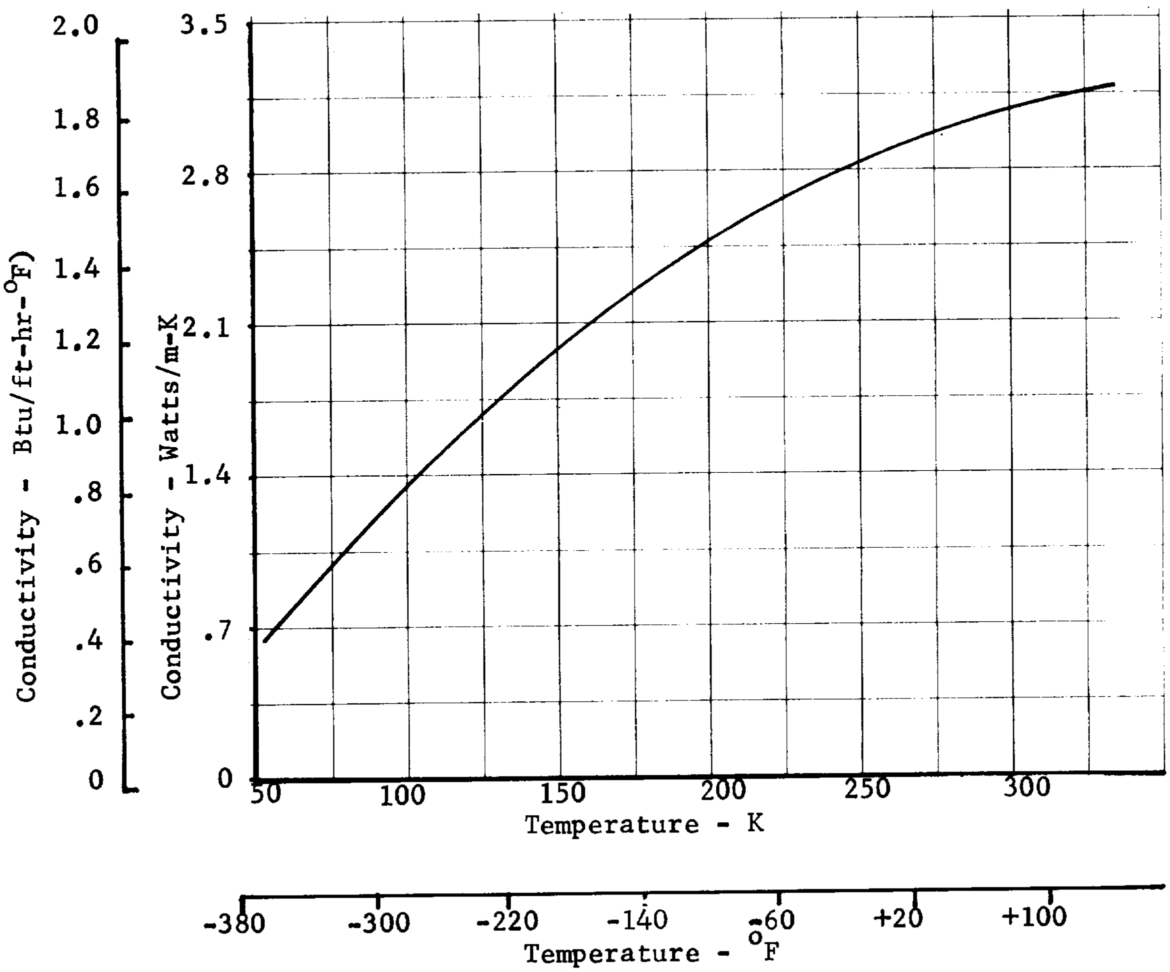


Figure D-4. - Thermal Conductivity of Composite Feedline in Axial Direction

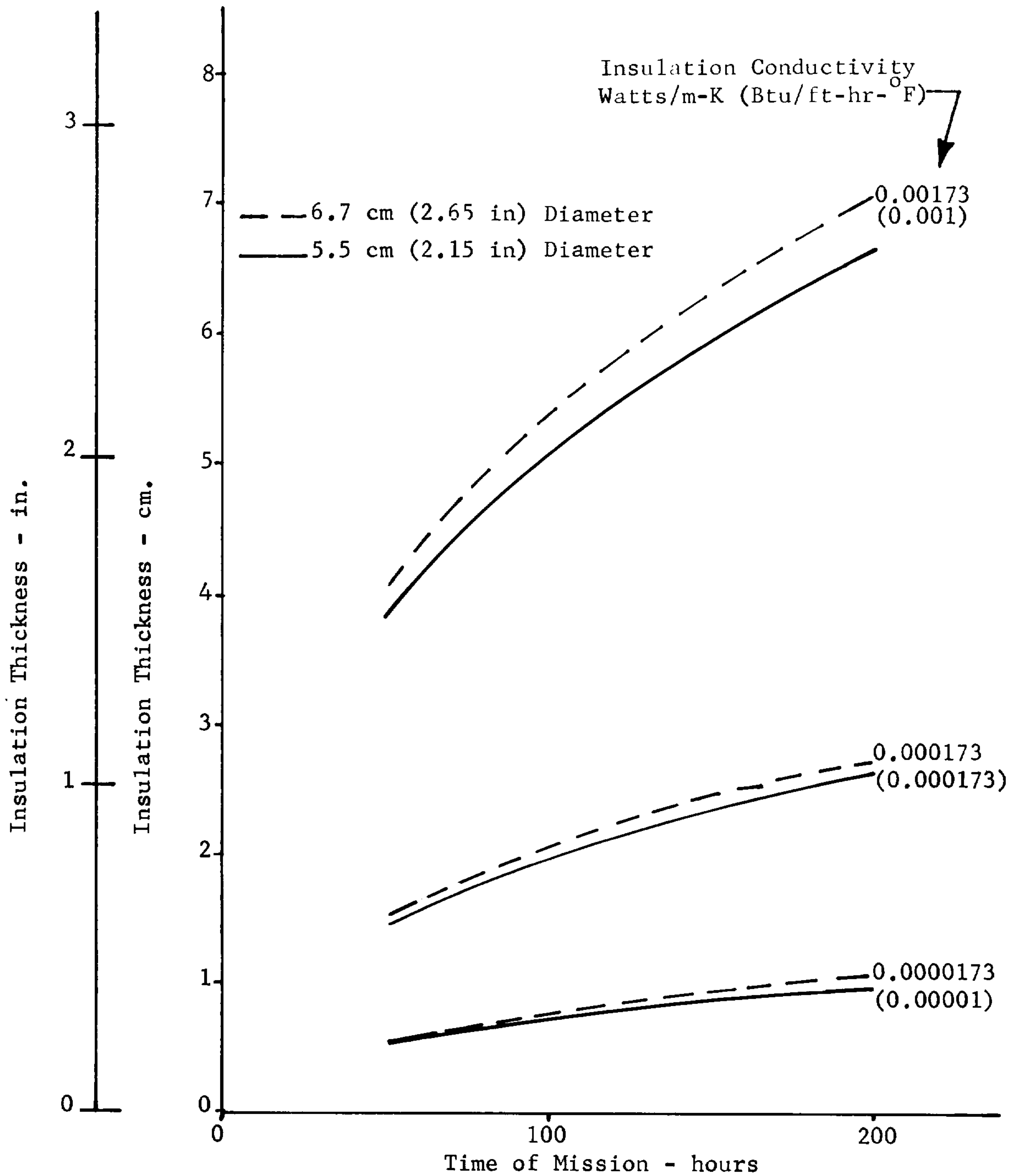


Figure D-5. - Optimum Insulation Thickness for Liquid Oxygen Feedline with a Surface Temperature of 278 K (40°F)

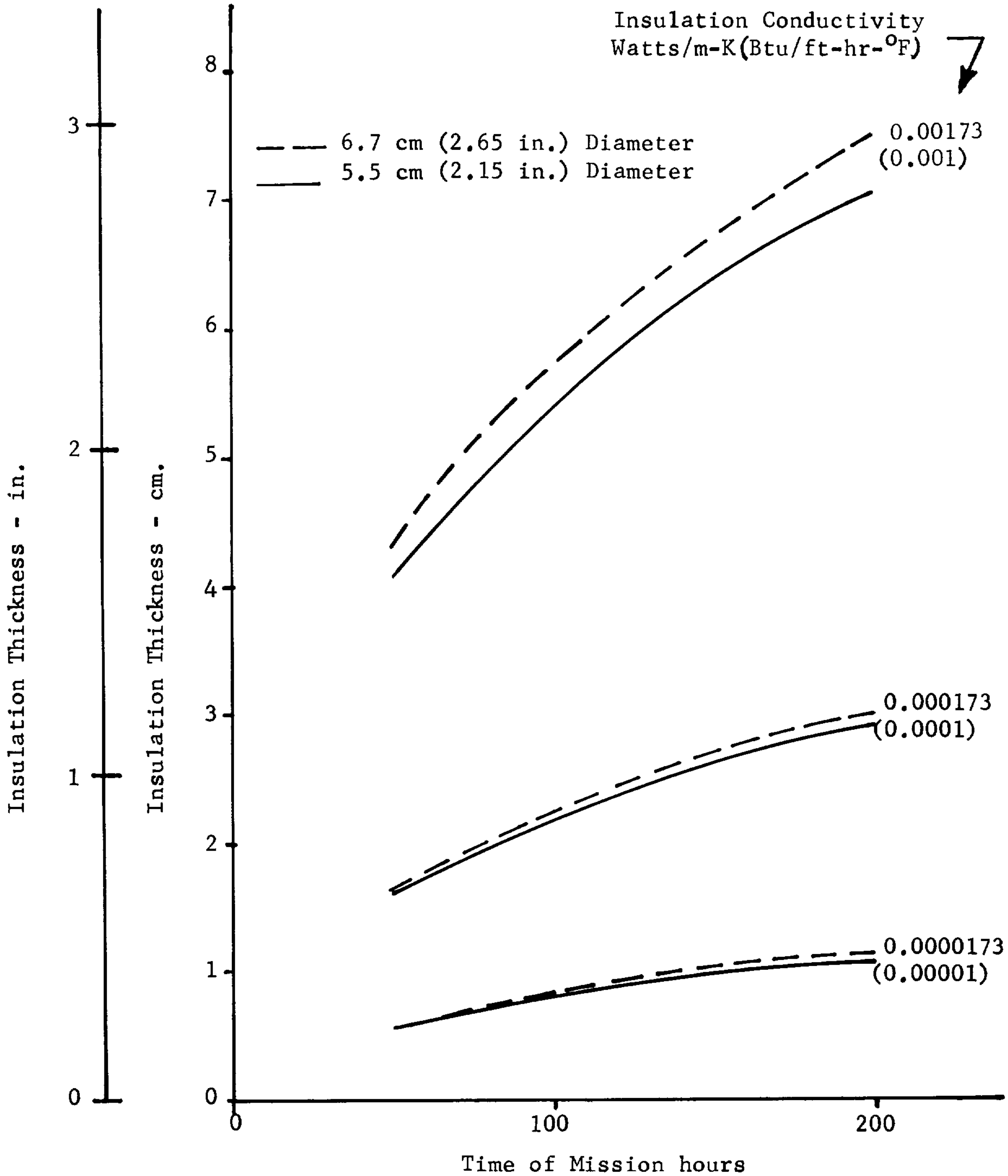


Figure D-6. - Optimum Insulation Thickness for Liquid Oxygen Feedline with a Surface Temperature of 317 K (110°F)

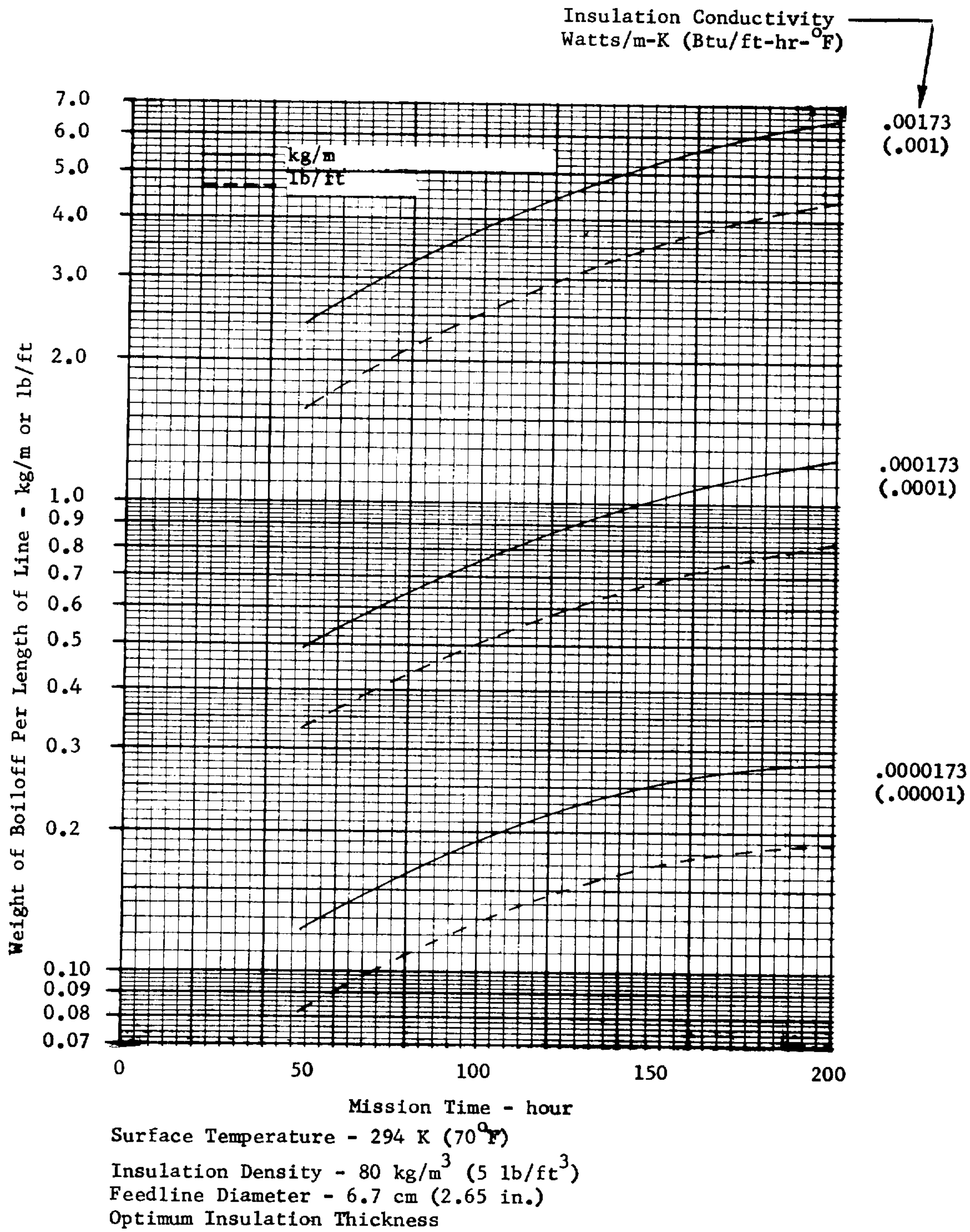


Figure D-7. - Effect of Insulation Conductivity on Liquid Oxygen Boiloff.

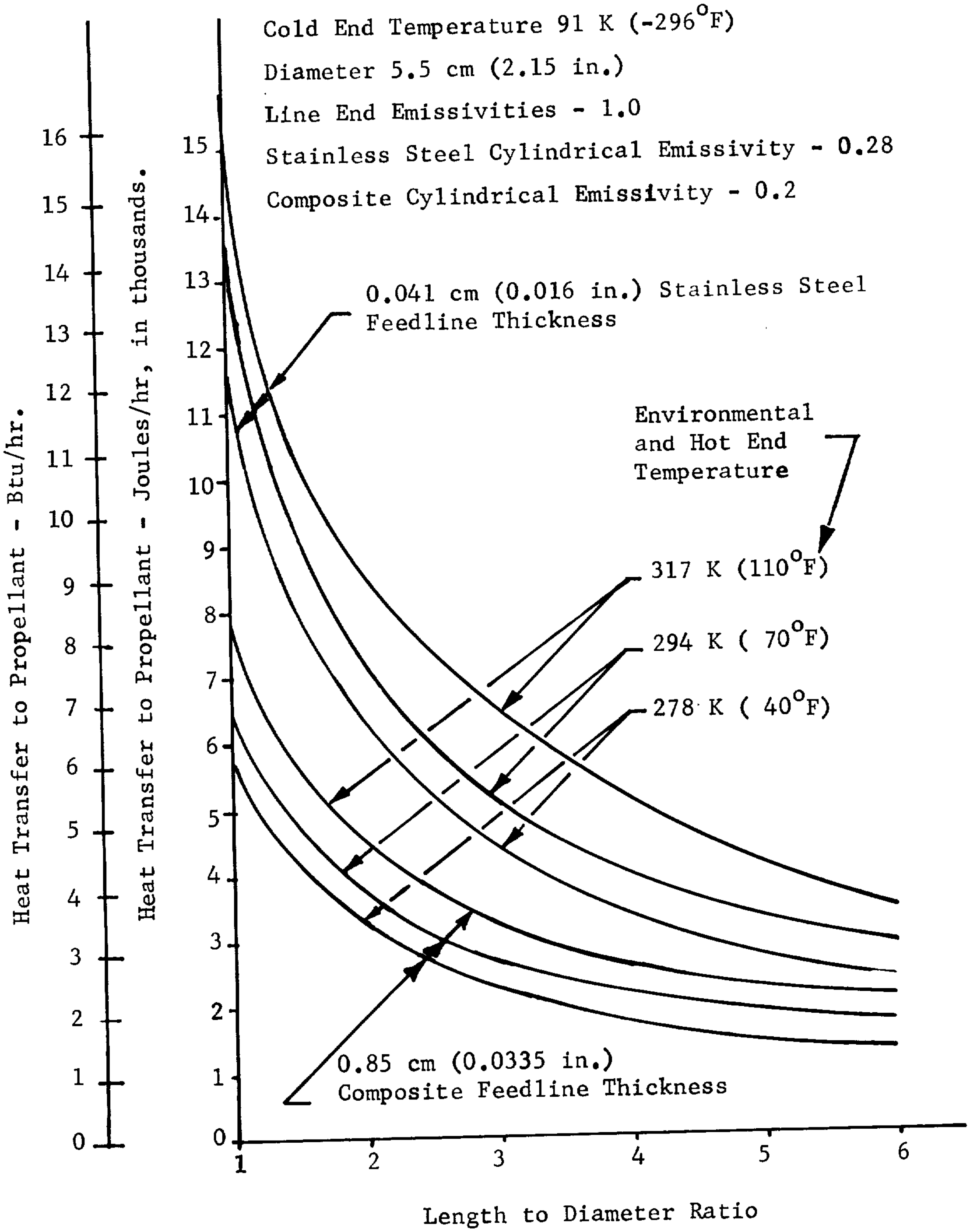


Figure D-8. - Heat Tranfer to Liquid Oxygen for Insulated Feedline End Section

Environmental Temperature - 294 K (70°F)
Hot End Temperature - 294 K (70°F)
Cold End Temperature -91 K (-296°F)
End Emissivity - 1.0
Diameter 5.5 cm (2.15 in.)
Feedline Thickness - 0.041 cm (0.016 in.)
Material - Stainless Steel

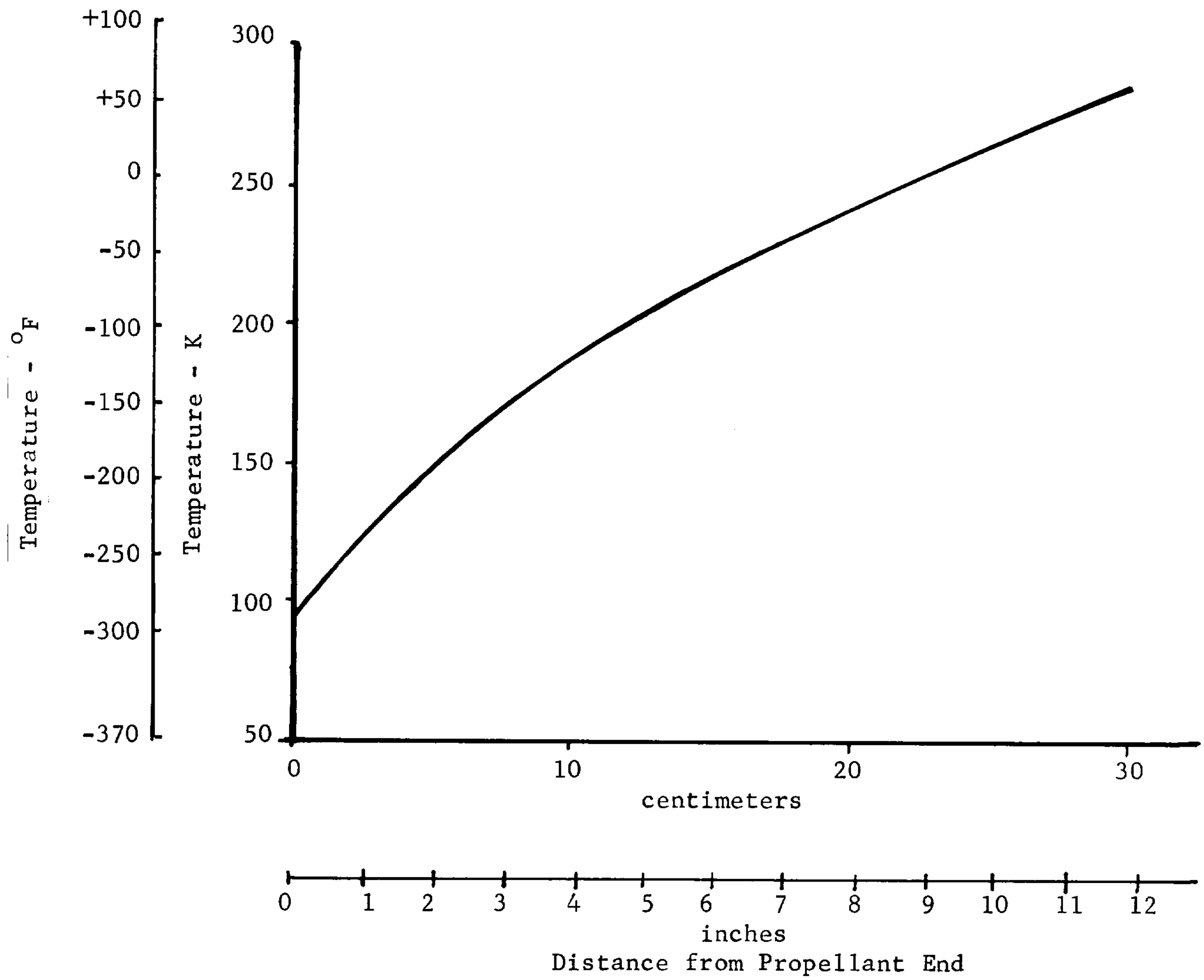


Figure D-9. - Typical Temperature Distribution for Insulated Feedline End Sections of All-metal Line

where

A = Surface area, in cm^2

C = Joint coefficient, in cm^2/cm

L = Joint length, in cm

T_c = Cold side temperature, in K

T_h = Hot side temperature, in K

e_j = Joint effective emissivity

σ = Stefan-Boltzmann constant, in $W/(m^2)(K^4)$.

For the flight configured system, the propellant loss due to joints was predicted to be 2.3 kg (5 pounds).

Vacuum jacketed feedline: The heat transfer to the vacuum jacketed feedline is by radiation from the vacuum jacket, heat transfer to the propellant by the dry end section and heat transfer thru the vacuum jacket supports. Since the feedline is protected from the environment by the vacuum jacket, both the composite and all-metal feedlines were assumed to have a surface emissivity of 0.026.

Heat transfer to the main body of the all-metal feedline was calculated from the equation

$$Q = A_1 \mathcal{F}_{12} \sigma (T_2^4 - T_1^4);$$

where

Q = Total heat transfer, in watts

A_1 = Surface area of feedline, in m^2

A_2 = Surface area of vacuum jacket, in m^2

$\mathcal{F}$ = Radiation interchange factor which is defined as

$$\mathcal{F}_{12} = \frac{1}{\frac{1}{e_1} + \left(\frac{A_1}{A_2}\right)\left(\frac{1}{e_2} - 1\right)}$$

T_1 = Temperature of feedline, in K

T_2 = Temperature of vacuum jacket, in K

e_1 = Emissivity of feedline

e_2 = Emissivity of vacuum jacket

σ = Stefan-Boltzmann constant, in $W/(m^2)(K^4)$.

However, in the case of the composite feedline which has a gap, a heat balance gave the equation:

$$A_o f_{ov} \sigma (T_v^4 - T_o^4) = A_o f_{oL} \sigma (T_o^4 - T_L^4)$$

$$f_{ov} = \frac{1}{\frac{1}{e_o} + \left(\frac{A_o}{A_v}\right)\left(\frac{1}{e_v} - 1\right)}$$

$$f_{oL} = \frac{1}{\frac{1}{e_o} + \frac{1}{e_L} - 1}$$

where

A_o = Surface area of feedline, in m^2

A_v = Surface area of vacuum jacket, in m^2

T_o = Temperature of overwrap, in K

T_L = Temperature of liner, 91 K

T_v = Temperature of vacuum jacket, 294 K

e_L = Emissivity of Inconel liner, 0.2

e_o = Emissivity of overwrap, 0.026

e_v = Emissivity of vacuum jacket, 0.28

σ = Stefan-Boltzmann constant, in $W/(m^2)(K^4)$.

The temperature of the overwrap can be determined as

$$T_o = \left[\frac{\mathcal{F}_{ov} T_v^4 + \mathcal{F}_{oL} T_L^4}{\mathcal{F}_{ov} + \mathcal{F}_{oL}} \right]^{1/4}$$

and the heat transferred by radiation from the vacuum jacket is

$$Q = A_o \mathcal{F}_{ov} \sigma (T_v^4 - T_o^4).$$

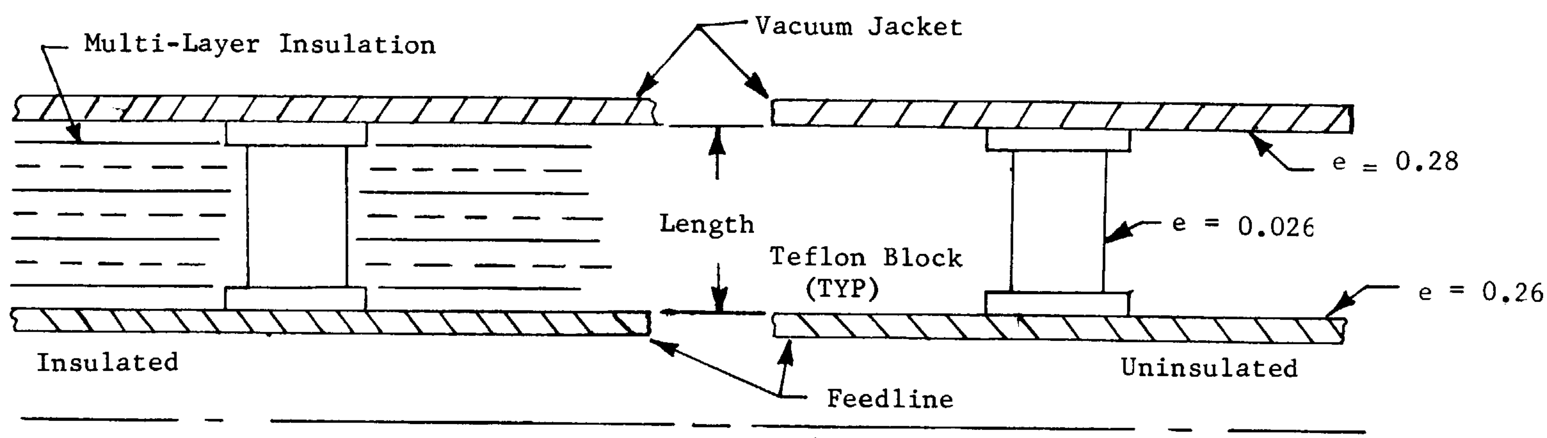
The composite feedline was again assumed to have 50% gap and 50% good contact between the liner and overwrap. Empirical data generated during the program indicates this to be a very conservative assumption with respect to the gap percent.

The vacuum jacket supports are shown in Figure D-10 and the heat transfer for each support is given in this figure. The support used in this case, with no insulation, was assumed to be coated with aluminum and polished. This gave an emissivity of 0.026. This low emissivity minimized the heat transfer by the vacuum jacket to the support. The vacuum jacket supports were placed every 91 cm (36 in.) with four at each location spaced 90° apart.

The feedline end for the vacuum jacketed case was modeled with a view factor program (MTRAP) and a thermal analyzer. The nodal arrangement is shown in Figure D-11. A highly reflective end was used upstream to reflect radiation. Results of the analysis are included in Table D-1.

Vacuum jacketed feedline with insulation: The heat transfer to the feedline for this system is by conduction through the insulation, heat transfer by the insulation joints, heat transfer by the vacuum jacket supports and heat transfer to the propellant by the feedline dry section. The analysis for this system is similar to the insulated, unjacketed feedline with the exception of the vacuum jacket support. The heat transfer by these supports is shown in Figure D-10. The insulation thickness for this case was taken as the spacing between the vacuum jacket and the feedline. Results of the analysis are included in Table D-1.

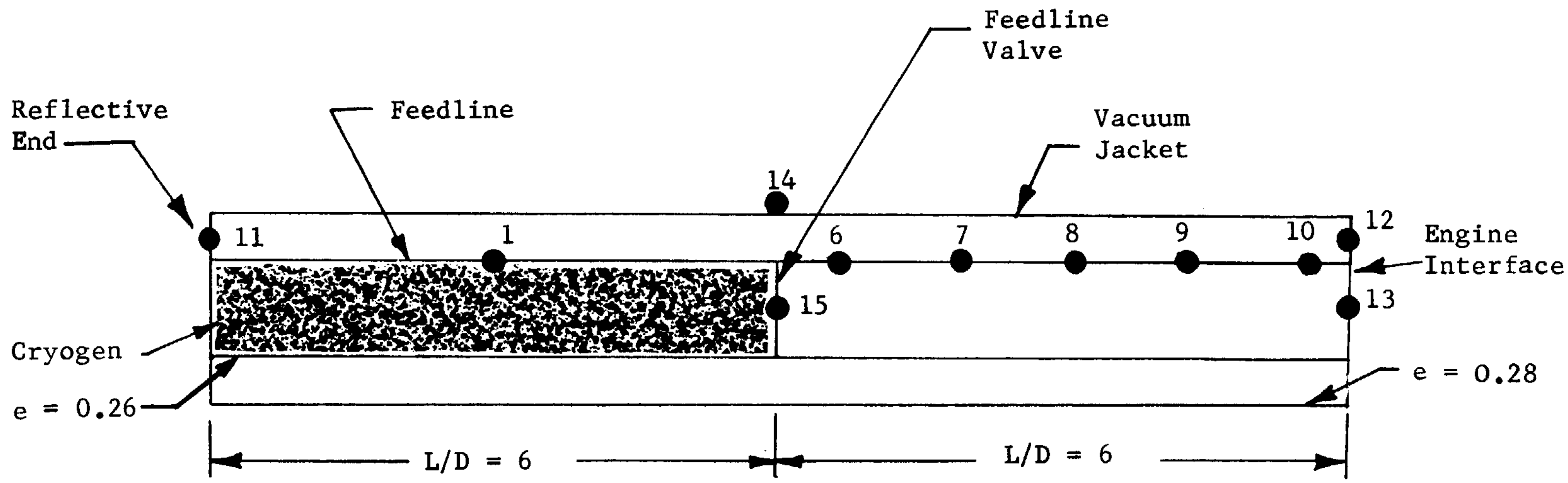
LOX OMS system emissivity optimization: An optimization study was performed to determine surface emissivity values within a vacuum annulus on the LOX flight configured feedline to minimize the radient heat transfer in the radial direction. The following paragraphs show the analysis performed and the equations used in this study.



Heat Rate - Watts (Btu/hr)		
Length	Uninsulated	Insulated
4.140 cm (1.63 in.)	0.516 (1.76)	0.513 (1.75)
3.89 cm (1.53 in.)	0.551 (1.88)	0.548 (1.87)

Vacuum Jacket Support - Stainless Steel
Support Diameter - 0.63 cm (0.25 in.)
Support Wall Thickness - 0.05 cm (0.02 in.)
Environmental Temperature - 294 K (70°F)
e - Emissivity

Figure D-10. - Vacuum Jacket Support Heat Transfer Rate to Liquid Oxygen Feedline



LOX	Feedline Diameter = 5.5 cm (2.15 in.) Vacuum Jacket Diameter = 13.2 cm (5.21 in.)
LH_2	Feedline Diameter = 7.9 cm (3.10 in.) Vacuum Jacket Diameter = 9.9 cm (3.90 in.)

Figure D-11. - Nodal Arrangement for Engine End of Vacuum Jacketed Feedline

Nomenclature -

A = Surface area, cm^2

D = Diameter, cm

τ = Configuration factor

$\mathscr{F}$ = Radiation interchange factor

L = Length, cm

R = Diameter ratio $(^{DI}/DO)$

β = Radiation absorption factor

e = Surface emissivity and absorptivity for infrared radiation

T = Temperature, K

σ = Stefan-Boltzmann constant, in $W/(m^2)(K^4)$

Q = Total radiation heat transfer, in watts

I = Inner line

O = Outer line (vacuum jacket).

Analysis -

$$\beta_{OI} = e_I \tau_{OI} + (1 - e_O) \tau_{OO} \beta_{OI} + (1 - e_I) \tau_{OI} \beta_{II} \tag{1}$$

$$\beta_{II} = e_I \tau_{II} + (1 - e_O) \tau_{IO} \beta_{OI} + (1 - e_I) \tau_{II} \beta_{II} \tag{2}$$

$$\tau_{IO} = 1 \tag{3}$$

$$\tau_{OI} = \tau_{IO} A_I/A_O = \pi D_I L/\pi D_O L = D_I/D_O = R \tag{4}$$

$$\tau_{OO} = 1 - \tau_{OI} = 1 - R \tag{5}$$

$$\tau_{II} = 0. \tag{6}$$

Substituting (3) and (6) into (2),

$$\beta_{II} = (1 - e_0)\, \beta_{0I}. \tag{7}$$

Substituting (4), (5) and (7) into (1),

$$\beta_{0I} = e_I R + (1 - e_0)(1 - R)\, \beta_{0I} + (1 - e_0)(1 - e_I) R\, \beta_{0I}. \tag{8}$$

Collecting terms and solving for β_{0I},

$$\beta_{0I} = \frac{e_I R}{1 - (1 - e_0)(1 - R) - (1 - e_0)(1 - e_I) R}. \tag{9}$$

But,

$$f_{0I} = e_0\, \beta_{0I} = \frac{e_0 e_I R}{1 - (1 - e_0)(1 - R) - (1 - e_0)(1 - e_I) R}. \tag{10}$$

Expanding the denominator, simplifying and dividing by e_0 e_I yields

$$f_{0I} = \frac{R}{\frac{1}{e_I} + \frac{R}{e_0} - R}. \tag{11}$$

To minimize the radiant heat transfer radially across the vacuum annulus, f_{0I} must be minimized. Examination of equation (11) shows that f_{0I} is minimized when both e_0 and e_I are minimized.

The equation for the heat transferred across the vacuum annulus by radiation is,

$$Q_{0I} = \sigma A_0\, f_{0I}\, (T_0^{\,4} - T_I^{\,4}). \tag{12}$$

Equation (12) indicates that Q_{0I} may be minimized by

- o Minimizing f_{0I} as discussed above;
- o Minimizing the vacuum jacket temperature, T_0 which can be accomplished by insulating the outside of the vacuum jacket and/or minimizing the emissivity of the outer surface;

- Minimizing the emissivity of the inner line by providing a thermal coating or one layer of double aluminized mylar insulation to the uninsulated configuration.

OMS LOX Steady-State Heat Input Test Configuration. - The LOX test configuration was evaluated thermally in three configurations including uninsulated, insulated and with a covering sufficient to provide effective emissivity control. The 98 node thermal model for the OMS LOX test item configuration was defined and form factors were obtained from the MTRAP computer program. An isometric view of the MTRAP input model is shown in Figure D-12. The plot shown was obtained as a preliminary check to verify the coordinate locations of all surfaces prior to the final MTRAP run. The four main sections of line are noted and reference is made to the detailed nodal breakdown and conductor networks shown in Figures D-13 and D-14 for a typical line section.

The MTRAP punched output, which forms input to the final thermal analysis, was then added to existing cards to complete the MITAS input deck for the final run to yield the heat leak values.

Uninsulated feedline test item: The heat transfer to the uninsulated feedline was calculated to determine propellant boiloff rates. The feedline configuration is shown in Figure D-15. The assumptions were:

- Uniform vacuum tank wall temperature;
- Uniform surface properties of feedline;
- Infinite conductance between overwrap and liner;
- Feedline small compared to vacuum tank.

The heat rate to the feedline can be expressed as

$$Q = \sigma e_f A_f \left(T_w^4 - T_f^4\right)$$

where

Q = Total heat input, in watts

A_f = Surface area of feedline, in m^2

T_f = Temperature of feedline, in K

T_w = Vacuum tank wall temperature, in K

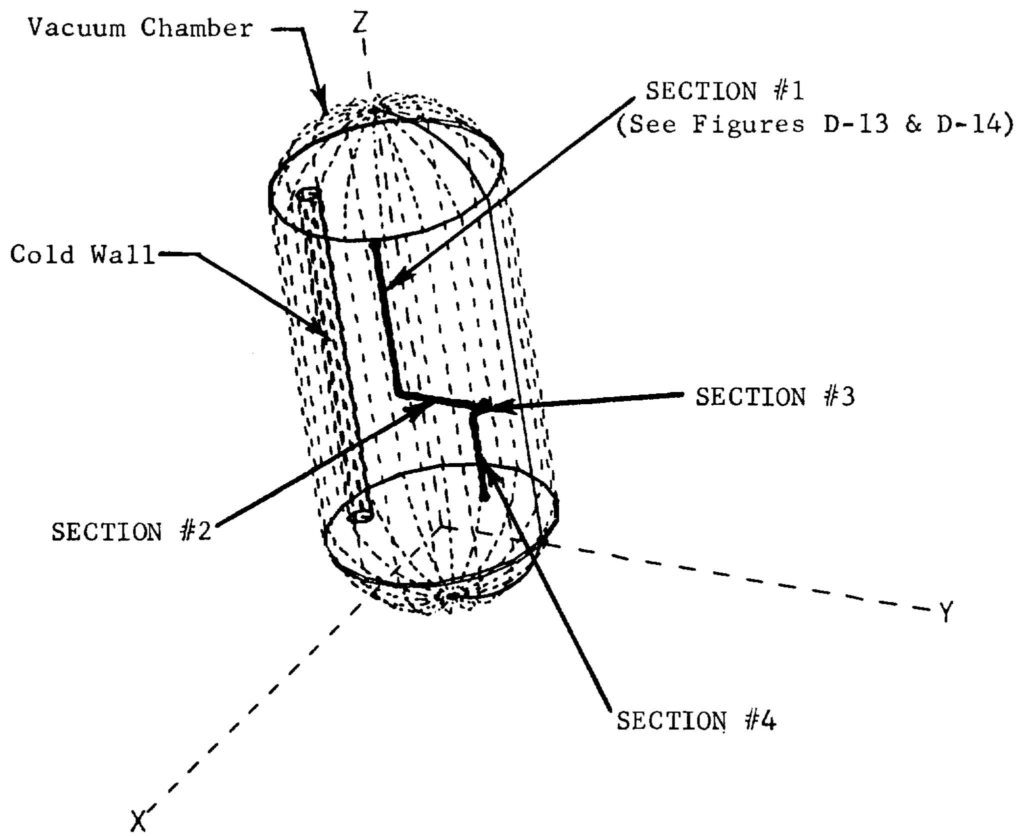
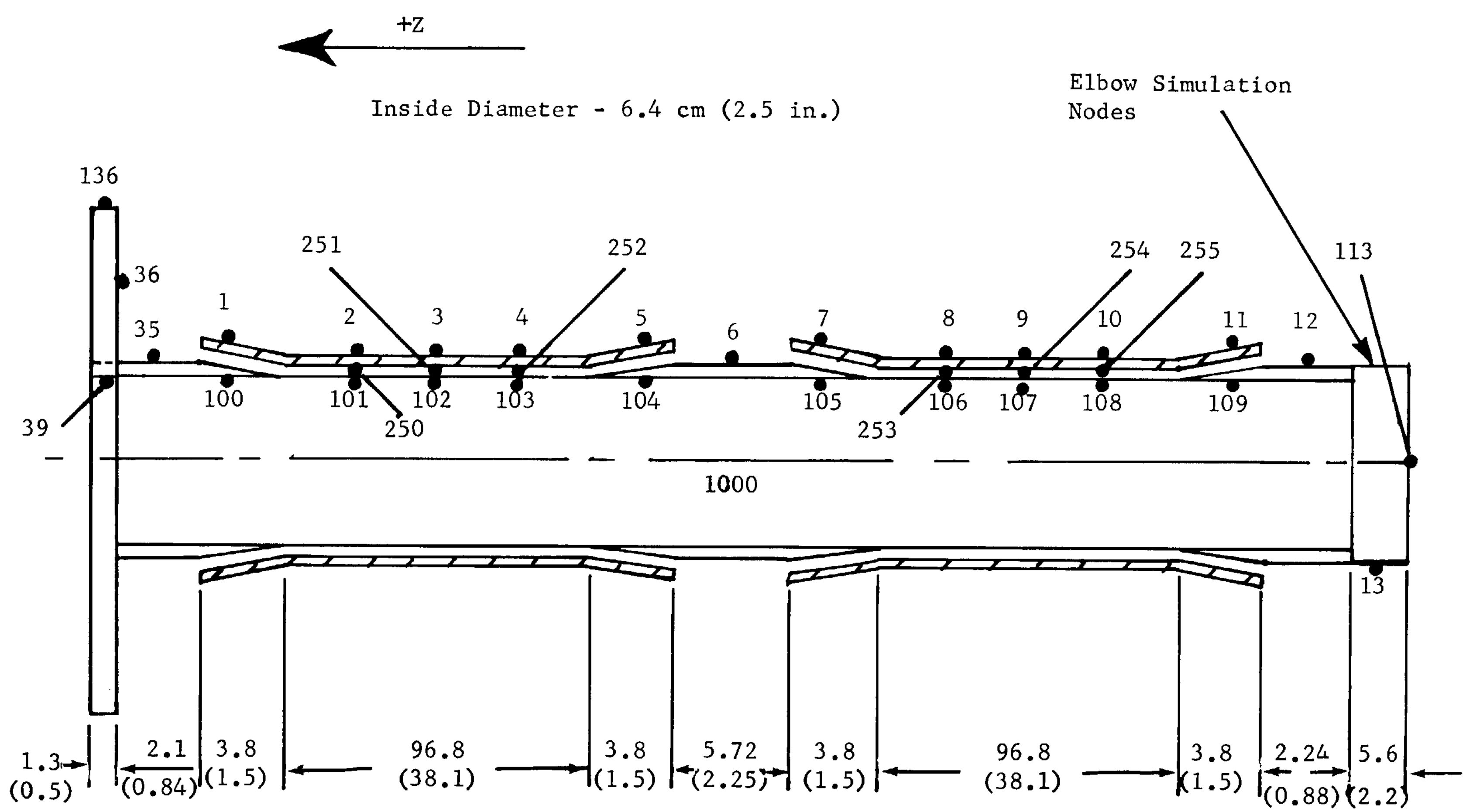
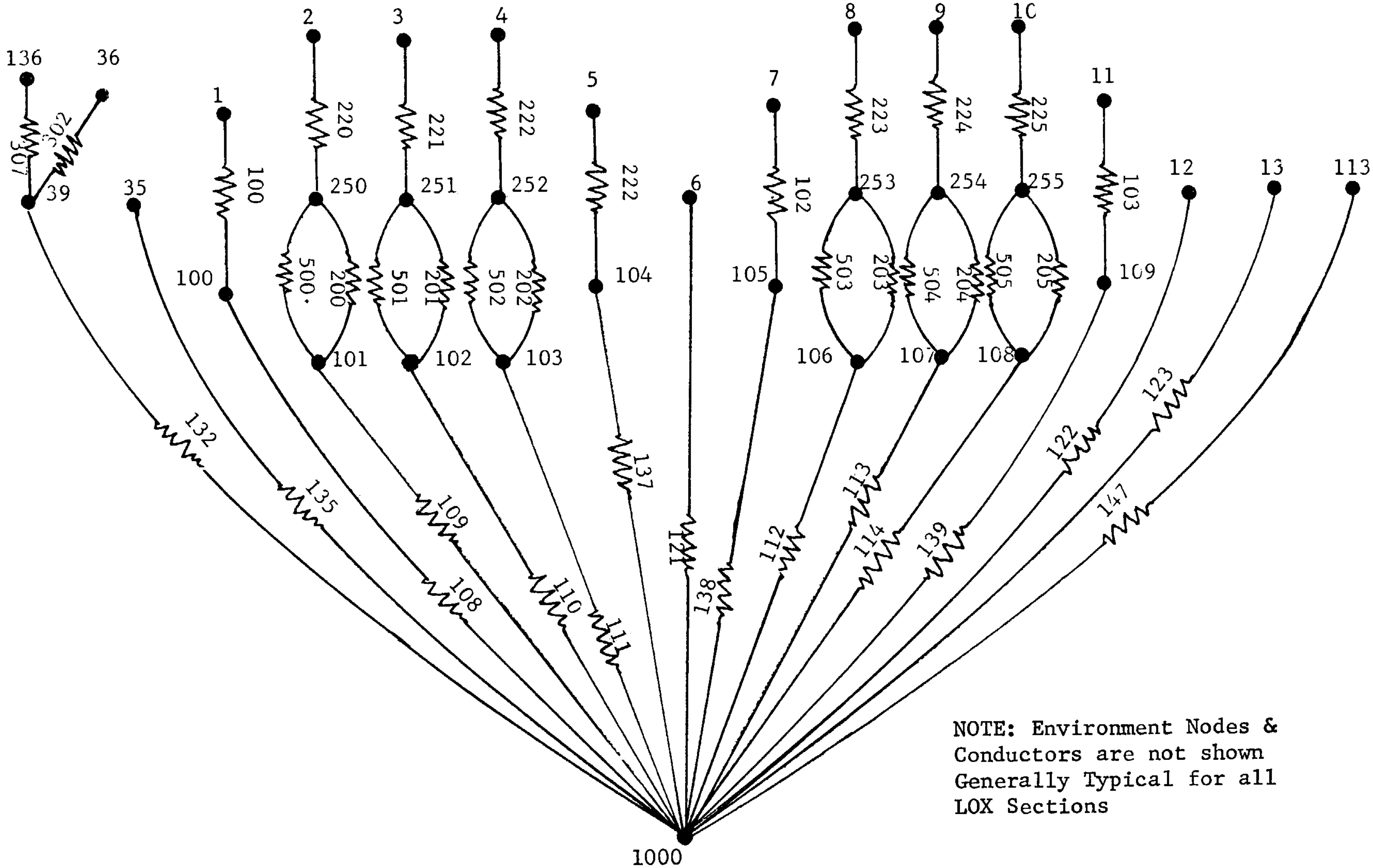


Figure D-12. - Steady State Heat Input Test Configuration
(Isometric View)



All Dimentions in cm (in.) Generally Typical for all LOX Sections

Figure D-13. - Nodal Breakdown for LOX Test Item Section #1



NOTE: Environment Nodes & Conductors are not shown Generally Typical for all LOX Sections

Figure D-14. - Node & Conductor Network for LOX Test Item Section #1

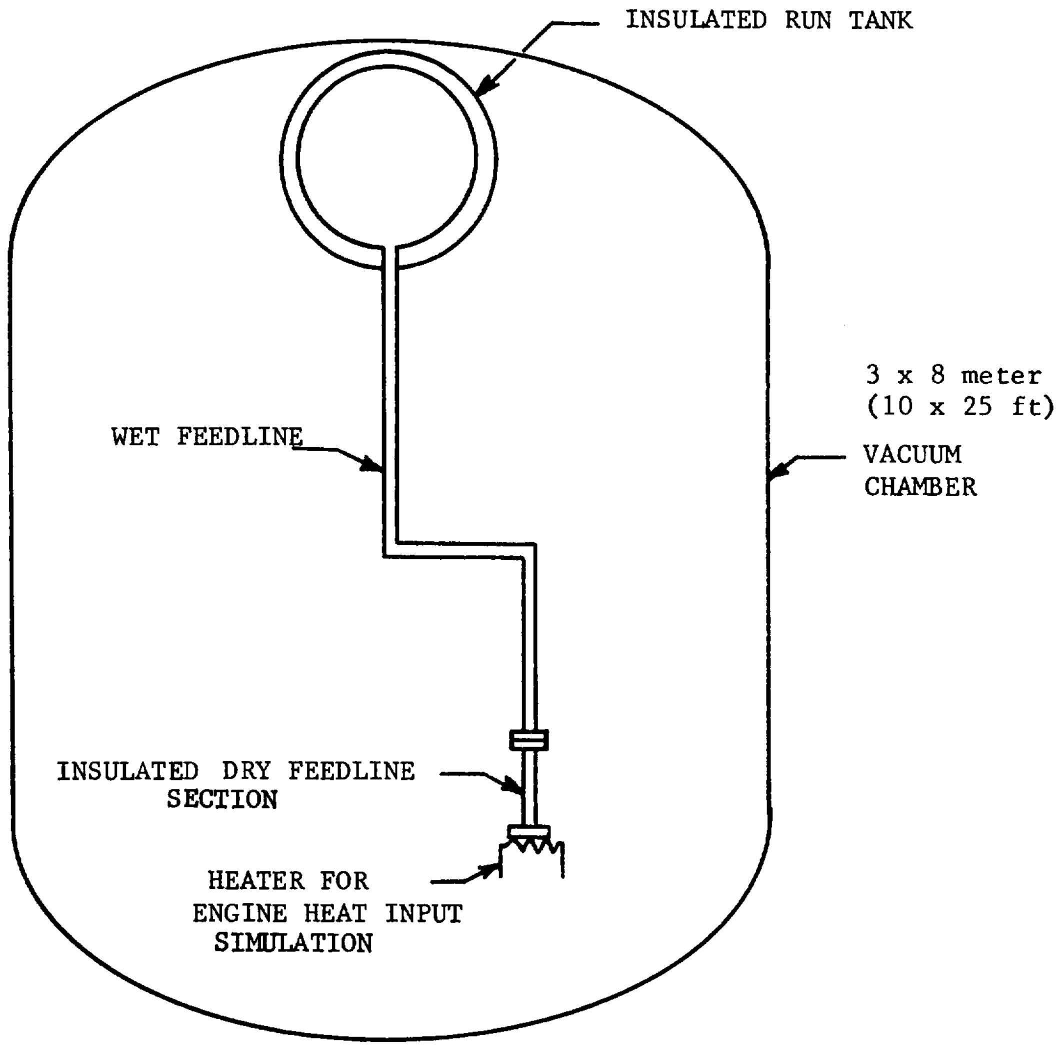


Figure D-15 - LOX Test Item Installed in Vacuum Chamber

e_f = Emissivity of feedline, a variable

σ = Stefan-Boltzmann constant, (5.67×10^{-8} W/m^2 K^4)

since $T_f^4 \ll T_w^4$

$$Q = \sigma e_f A_f T_w^4$$

The importance of knowing the tank wall temperatures and feedline emissivity can be seen from the above expression. The heat transfer rate calculated from this expression is shown in Figure D-16.

Insulated feedline test item: To determine the heat loss and the equilibrium times, the insulated feedline was modeled in the radial direction and input to the MITAS program. The insulation consisted of alternate layers of double aluminized mylar and nylon netting. Twenty layers were used. This combination at the desired compaction gave a thickness of 0.86 cm (0.34 in.). A conductivity of 1.4×10^{-4} W/m-K (8×10^{-5} Btu/ft-hr-$^\circ$F) was used and the heat loss from the feedline was predicted to be 4.1 watts (14 Btu/hr). For an insulation conductivity of 2.9×10^{-4} W/m-K (1.7×10^{-4} Btu/ft-hr-$^\circ$F) the heat loss is predicted to be 8.5 watts (29 Btu/hr).

The time required for the insulation mid-point temperature to come within 0.055 K (0.1°F) of steady state is six hours. At three hours, the mid-point temperature is within 1.1 K (2°F) of steady state. The mid-point temperature history is shown in Figure D-17 and the temperature distribution at six hours is shown in Figure D-18.

Vacuum required for test: The vacuum required in the vacuum chamber to eliminate heat transfer by convection which coincides with the molecular flow region requires about 0.0013 N/sq meter (10^{-5} torr). The position of the chamber in the molecular flow region at this vacuum level is indicated in Figure D-19.

The following chart (14) is helpful in determining the magnitude of convection as the pressure in the vacuum chamber rises above this ideal level. The rise is fairly insignificant below 1 N/sq m (10^{-2} torr). Higher vacuum allows for a substantial delta pressure across the insulation which is desirable.

$Q = e_f \, A_f \, \sigma \, T_w^{\,4}$

e_f = Emissivity of Feedline

A_f = Surface Area of Feedline

σ = Stefan Boltzmann Constant

T_w =Vacuum Tank Temperature = 294 K (70 ^{o}F)

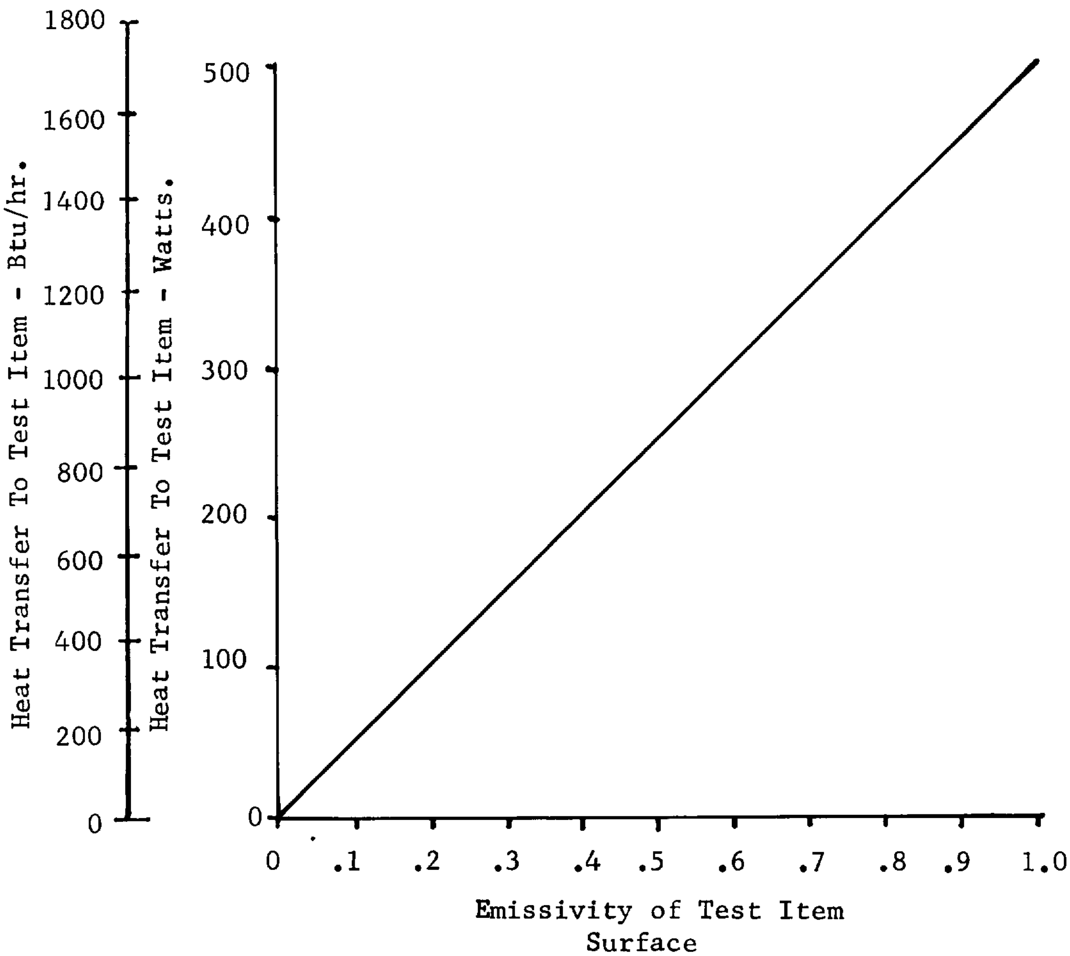


Figure D-16. - Heat Transfer to Uninsulated Test Item by Radiation

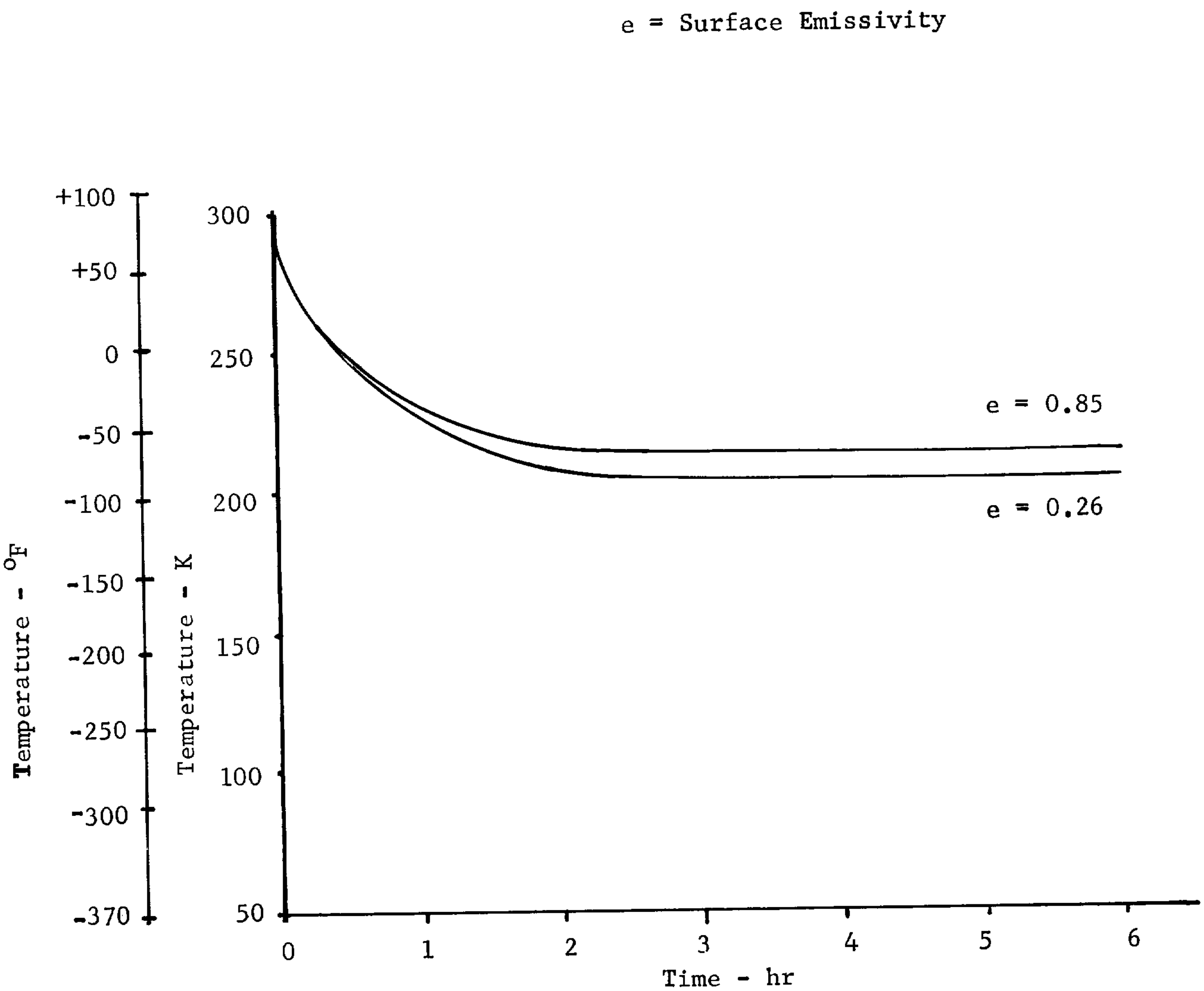


Figure D-17. - Midpoint Temperature of Insulation

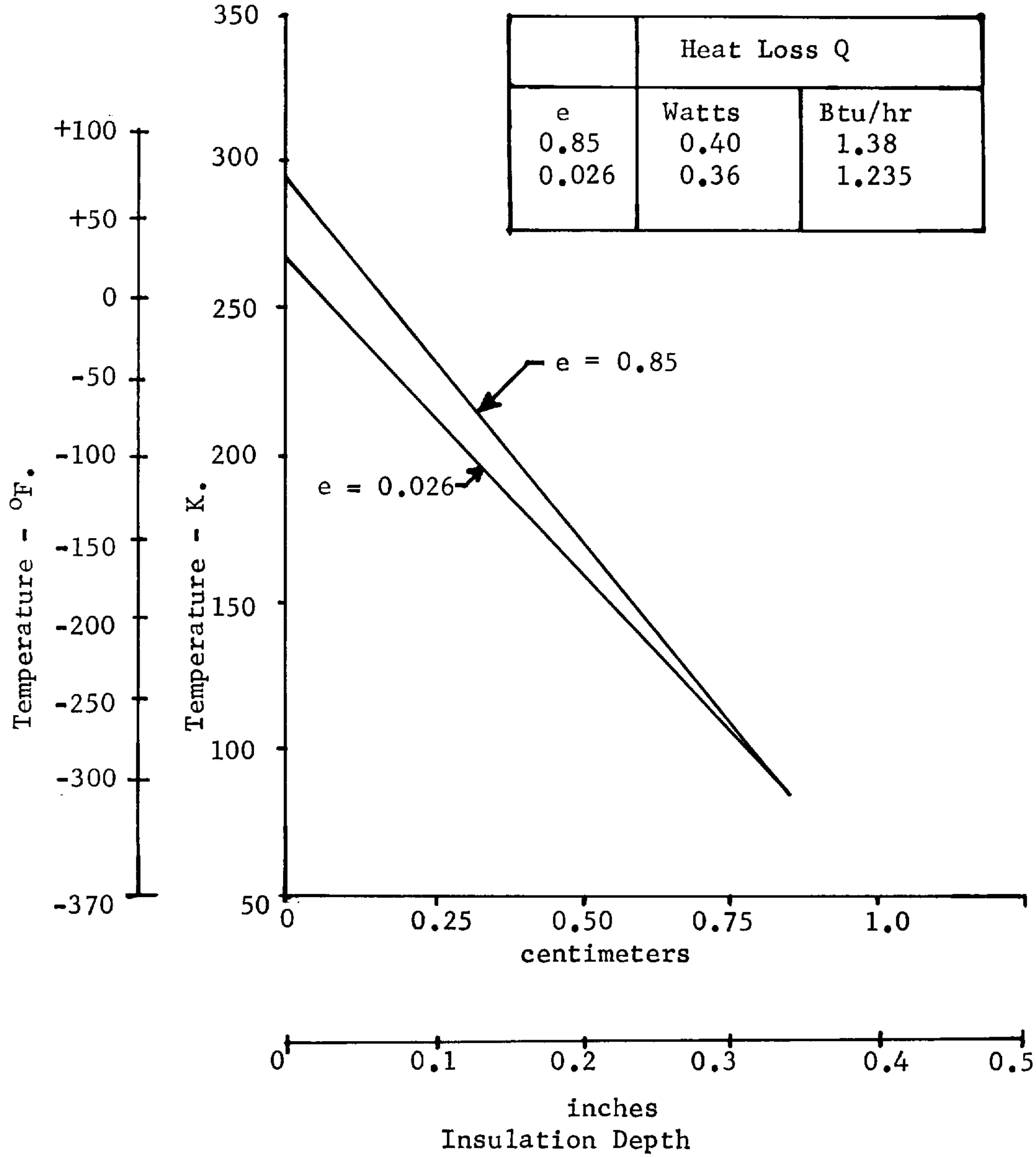


Figure D-18. - Temperature Distribution Through Insulation at 6 Hours

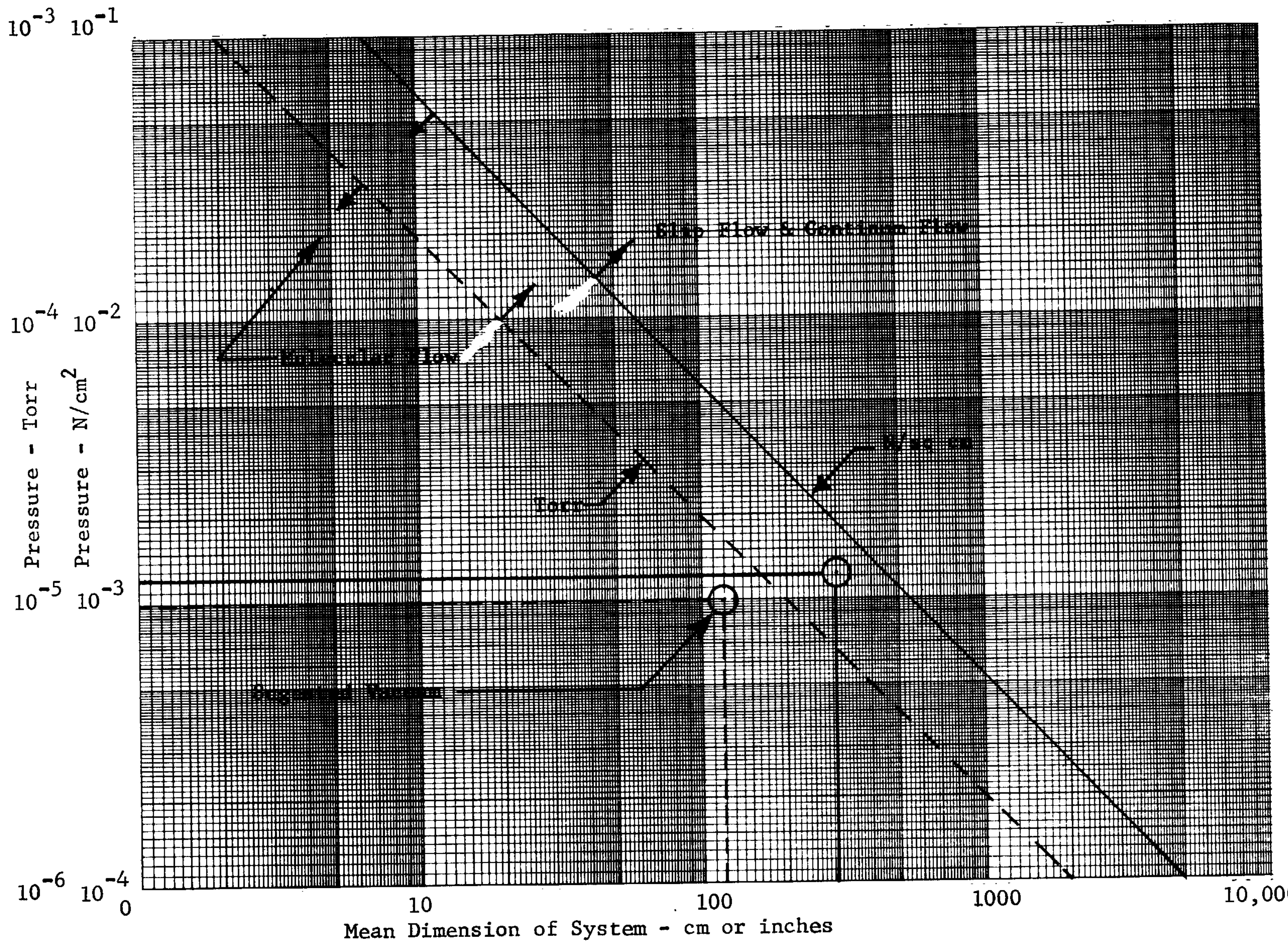
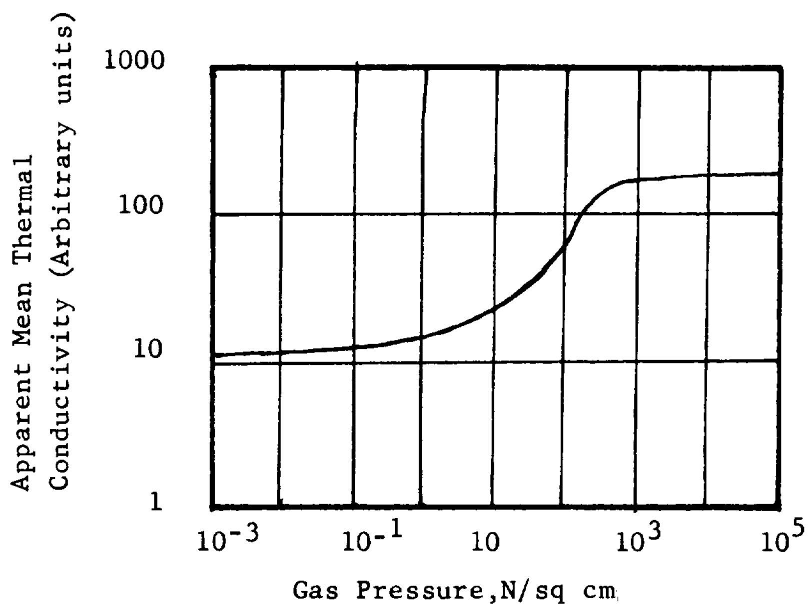


Figure D-19. - Vacuum Required for Molecular Flow Regime



Engine simulation: For the thermal effects of an engine on the feedline, it was necessary to consider typical designs of cryogenic feedlines. These designs are shown in Figure D-20 for a wet and for a dry feedline. The cryogen for the wet line would not be adjacent to the engine since this configuration would result in a large heat leak and boiloff. Therefore, thermal resistance is incorporated into the system by leaving part of the line dry.

The engine thermal effects are simulated by a length of dry line with a heater on the end of the dry line. The heat input to the feedline by the engine is shown in Figure D-21 as a function of the L/D and the engine temperature. The feedline is 6.4 cm (2.5 in.) diameter stainless steel with a wall thickness of 0.3 cm (0.12 in.). Since the length of the dry section is 30 cm (12 in.) and a typical engine temperature is 317 K (110°F), the heat input is about 6.2 Watts (21 Btu/hr). Both radiation and conductivity heat transfer were considered.

OMS LH_2 Steady State Heat Input. - This analysis was performed on the flight configuration of the OMS LH_2 feedline for each of the following conditions:

- o Jacketed composite line.
- o Jacketed all-metal line.

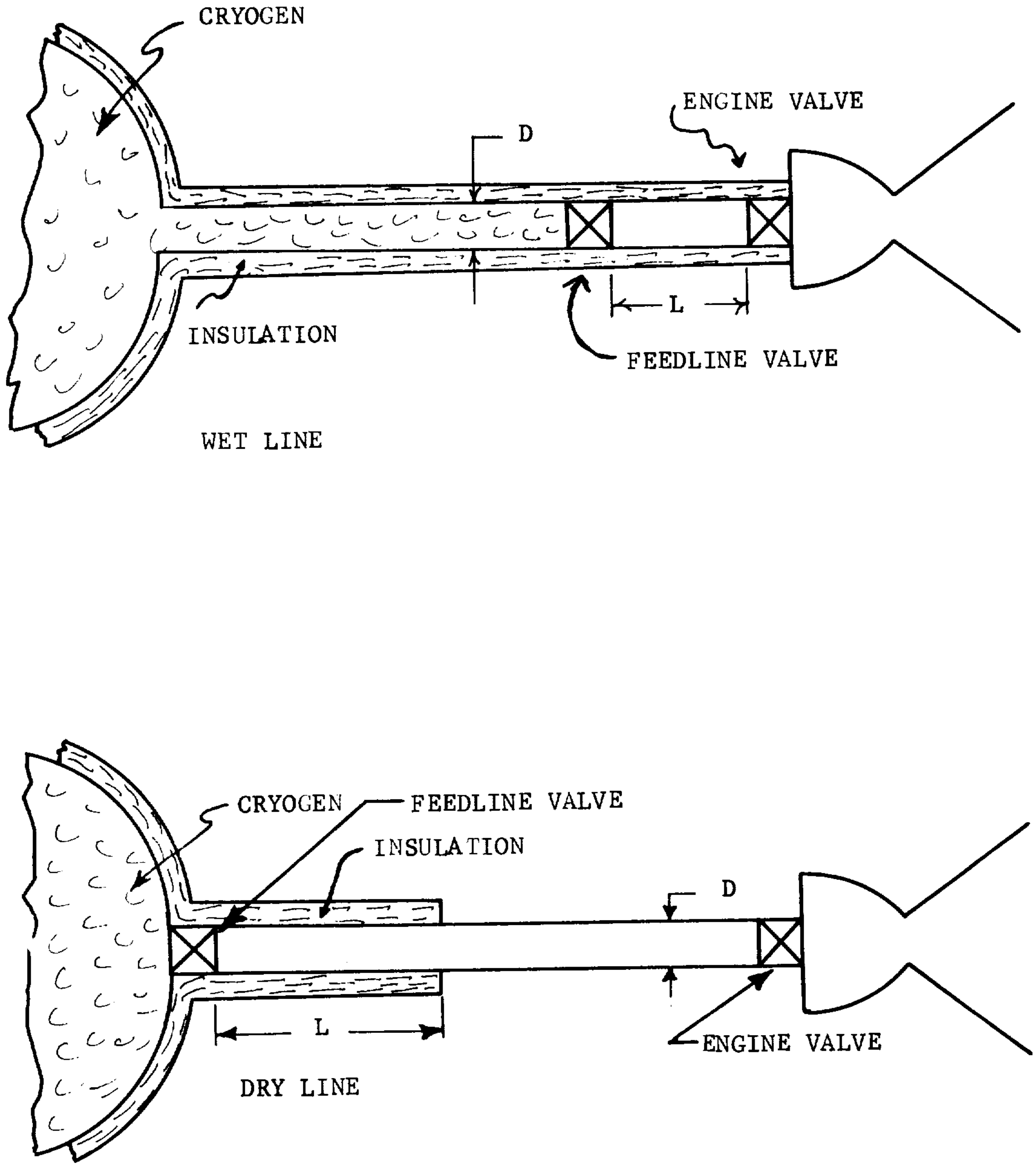


Figure D-20. - Thermal Design of Cryogenic Feedline for Minimum End-Heat-Leak

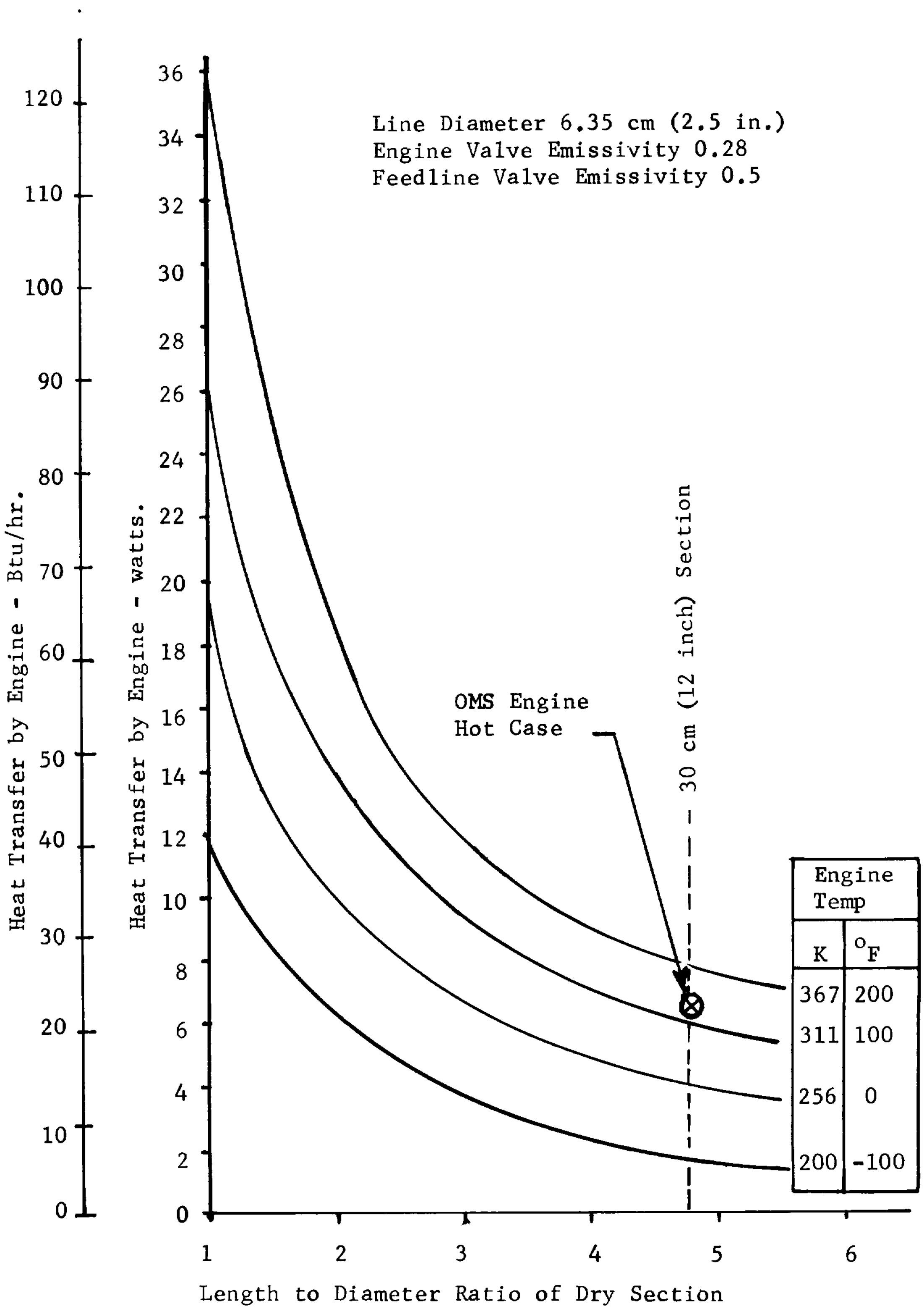


Figure D-21. - Heat Transfer by Engine to Feedline

- o Insulated and jacketed all-metal line.
- o Insulated and jacketed composite line

Since no steady-state heat input tests were planned for the LH_2 feedline, the test configuration of this line was not analyzed.

The analysis for the LH_2 feedline was performed using the same methods, equations and assumptions that were used in the LOX analysis.

Sketches indicating the two general configurations analyzed are shown in Figure D-20. The sketches may be somewhat misleading in that the wetted length represents approximately 51.8 meters (170 feet) of feedline. The analysis also includes the effect of all-metal lines versus composite lines. Through the ADTAP computer program, thermal end losses were determined for the insulated and jacketed composite feedline and the insulated and jacketed all-metal feedline. The results are plotted on Figure D-22. The nodal arrangement used for this model is similar to that shown on Figure D-13 and the conductor network is similar to the network shown in Figure D-14. The propellant losses determined from this analysis are summarized in Table D-2.

OMS/ACPS Flow Optimization. - The FLOWOPT computer program was used to optimize the size (diameter and weight) of the feedline for the orbiter OMS and ACPS systems. This analysis optimizes the total required weight of non-usable materials so as to minimize on-orbit weight. The non-usables or non-consummables include the basic system weights and propellants and gases expended without being used for thrust development. As the feedline diameter becomes larger, system pressure drops become smaller and pressure containing devices become lighter. The line (and vacuum jacket in some cases) becomes heavier. Additionally, the propellant required to cool the line will be increased and the boiloff of propellant in the line will also be increased due to larger surface areas. Using each component of the system as a variable, one can select the optimum configuration based upon a specific mission profile. A system configuration is shown in Figure D-23.

For purposes of this analysis, the number of engine restarts per mission (4, 2 or 1 spread widely from the first start), the required propellant quality at engine start (single phase liquid), and overall feedline geometries were those used in the Phase B baselined Shuttle study.

To arrive at the optimum feedline design, the following variables were evaluated for their effect on the above weight and performance factors.

Cold End Temperature 91 K (-296°F)
Diameter 5.5 cm (2.15 in.)
Line End Emissivities - 1.0
Stainless Steel Cylindrical Emissivity - 0.28
Composite Cylindrical Emissivity - 0.2

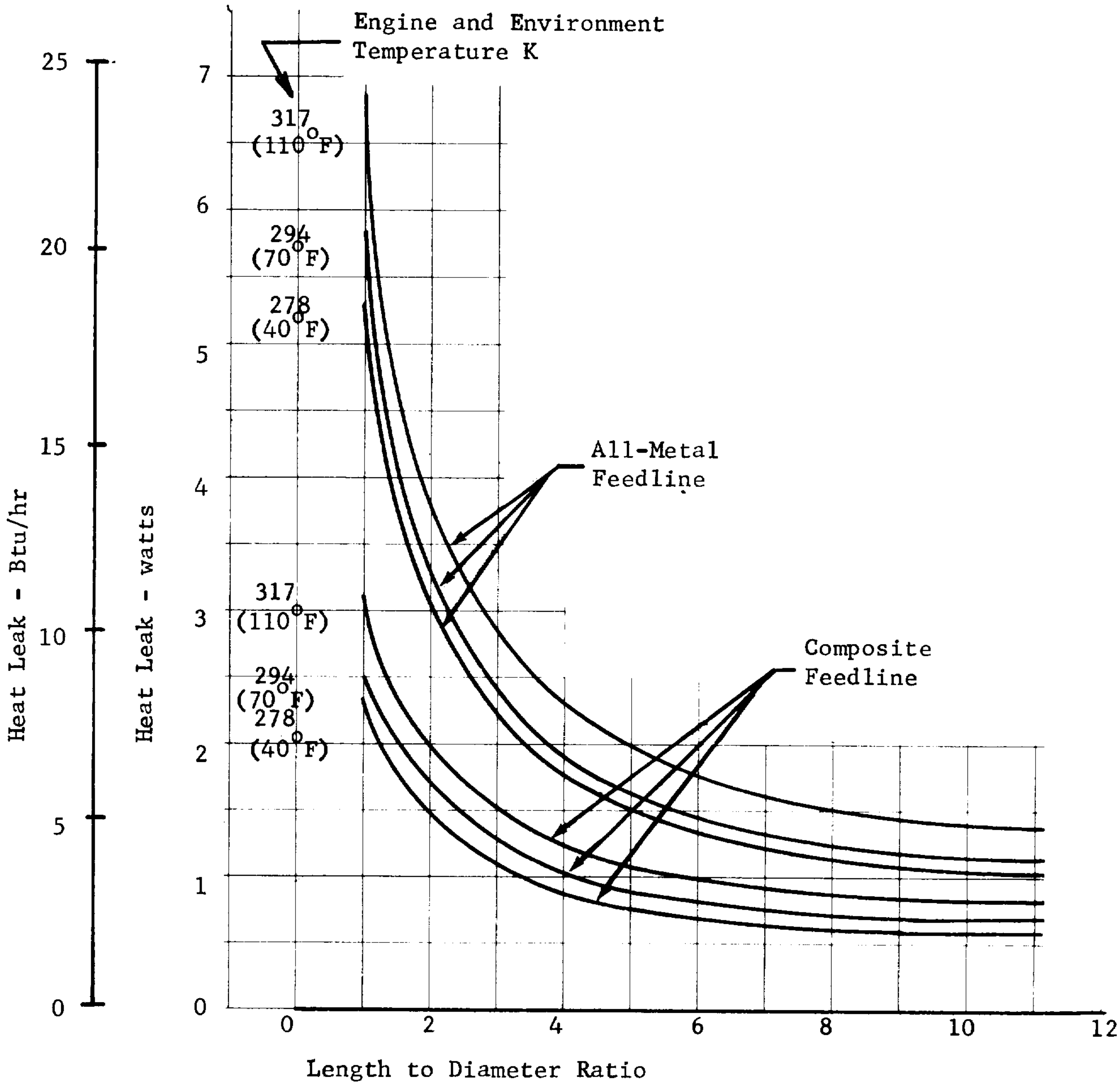


Figure D-22. - End Heat Leaks for the LH_2 Insulated and Vacuum Jacketed Feedline

Table D-2. - Summary of Propellant Losses Due to Boiloff For A 200 Hour Mission--LH_2 Feedline

Feedline Type	Thermal System	Radial Loss		Feedline End Loss		Vacuum Jacket Support Loss		Insulation Joint Loss		Total	
		kg	lb	kg	lb	kg	lb	kg	lb	kg	lb
All-Metal	Vacuum Jacket (NoInsulation)	kg 337	lb 743	kg * 9.5	lb * 21	kg 147	lb 325	kg --	lb --	kg 494	lb 1089
	Vacuum Jacket (With Insulation)	150	331	4.5	10	147	325	7.7	17	310	683
Composite	Vacuum Jacket (No Insulation)	329	726	* 7.7	* 17	147	325	--	--	484	1068
	Vacuum Jacket (With Insulation)	150	331	2.7	6	147	325	7.7	17	308	679

e = Surface Emissivity of Feedline = 0.026
L/D = Length to Diameter Ratio of Feedline End, Dry Section = 6
* - Boiloff Includes Wet Section Equal to Dry Section
Feedline End Loss Includes Two Engines

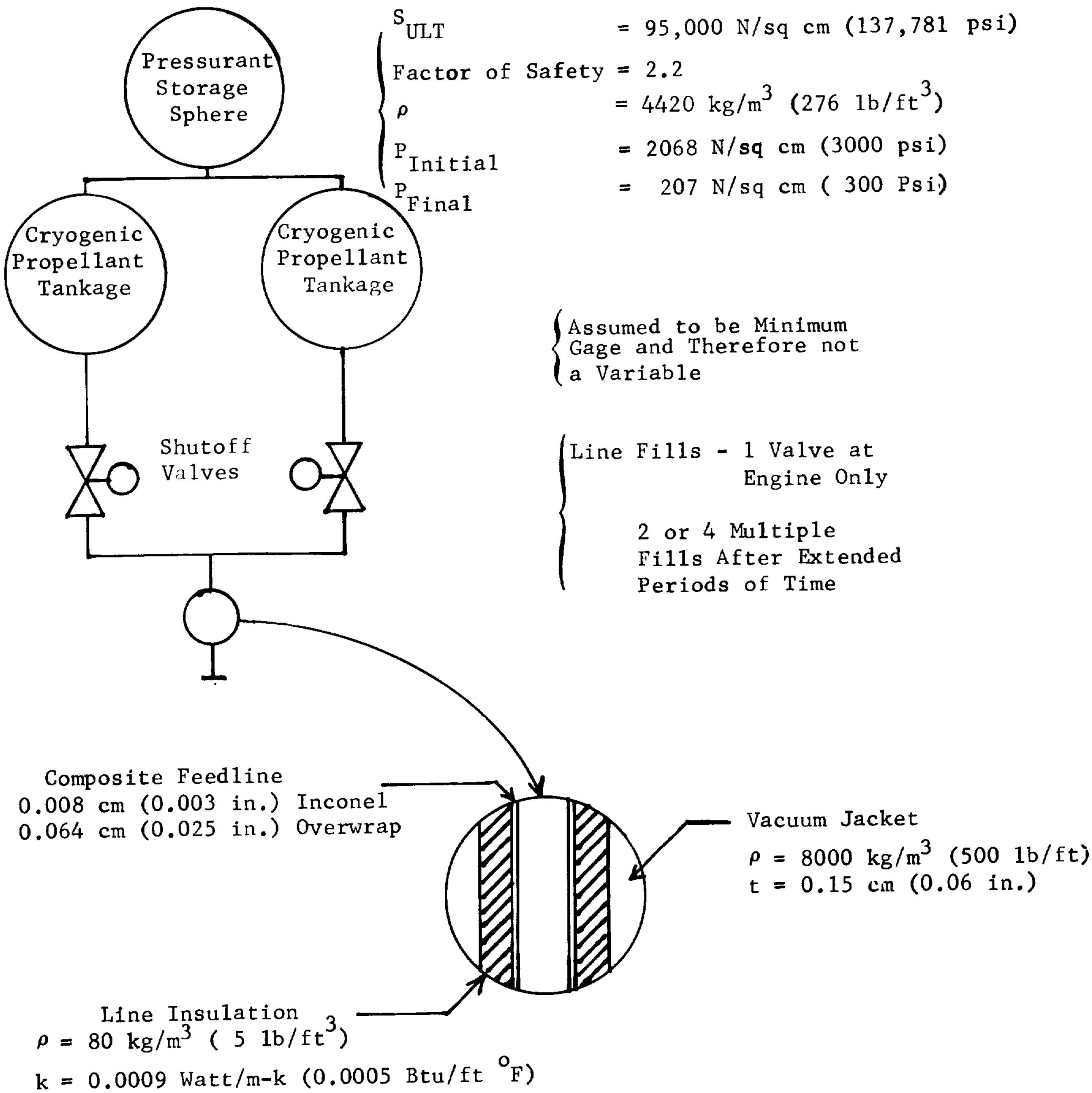


Figure D-23. - Configuration of Optimized OMS and ACPS Systems for LOX or LH_2

- o Feedline geometry including length using a two-dimensional study with a unit length of 30.5 cm (12 in.), the diameter which was variable from 2.5 to 18 cm (1 to 7 in.) and curvature which was assumed straight.
- o Material, structural and thermal properties.
- o Valve placement at tanks.
- o Insulation properties of K = 0.0009 watts/m-K (0.0005 Btu/ft$^{\circ}$F) and ρ = 80 kg/m^3 (5.00 lb/ft^3).
- o Boundary temperature of 289 K (60°F).

These performance trades are presented herein in a graphical presentation with accompanying clarifying tables.

Two different optimization techniques were used. The first, set a feedline diameter chosen to be 2.5 to 17.8 cm in 2.5 cm (1 to 7 in. in 1 in.) increments and then optimized the configuration using the following variables:

- o Insulation thickness;
- o Vacuum jacket thickness;
- o Number of line fills;
- o Flowrate of propellant;
- o Boiloff of propellant.

The second optimization technique utilized the simultaneous solution of two high order equations varying the insulating characteristics at the same time as the feedline diameter was varied over an infinite range. This resulted in an optimization of the total system weight which was plotted with the above data and shows the sensitivity of the system weight as a function of feedline diameter. Results are plotted on Figures D-24 through D-29 and Tables D-3 through D-8.

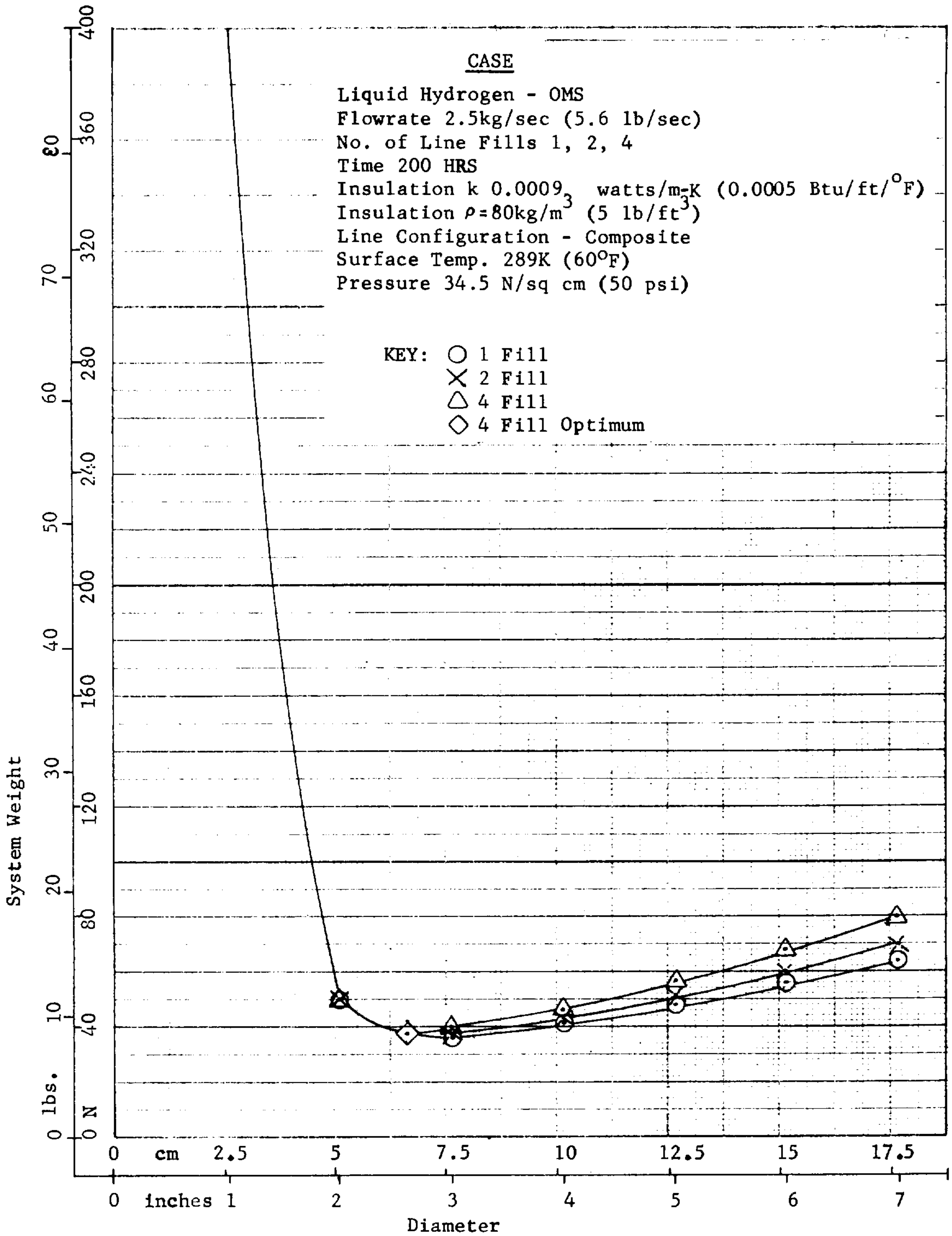


Figure D-24. - System Weight Optimization -- LH_2 OMS at Lower Flowrate

TABLE D-3. - SYSTEM WEIGHTS -- LH_2 OMS AT LOWER FLOWRATE

CASE

LIQUID HYDROGEN - OMS

Flowrate	2.5 kg/sec	(5.6 lb/sec)
No. of Line Fills		1
Time of Mission		200 hrs.
Insulation k	0.0009 watts/mK	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289K	(60°F)
Working Pressure	34.5 N/sq cm	50 psi

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	.36	1.44	3.23	5.76	8.99	12.95	17.62
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	2610.49	81.57	10.74	2.54	.83	.34	.15
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	2661.13	166.18	120.74	138.35	162.46	188.05	214.29
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	6.48	10.26	13.56	16.74	19.79	22.76	25.67
Insulation Tks(cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	574.54	17.93	2.34	.55	.21	.07	.07

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.024	0.097	0.217	0.387	0.604	0.870	1.184
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	175.436	5.482	0.722	0.171	0.056	0.023	0.010
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	179.175	11.108	8.115	9.298	10.918	12.638	14.401
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks(in)	0.747	0.980	1.142	1.266	1.367	1.452	1.524
ΔP/ft (lb/in^2)	833.3	26.0	3.4	0.8	0.3	0.1	0.1

TABLE D-3. - SYSTEM WEIGHTS -- LH_2 OMS AT LOWER FLOWRATE (CONT.)

CASE

LIQUID HYDROGEN - OMS

Flowrate	2.5 kg/sec	(5.6 lb/sec)
No. of Line Fills		2
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289K	(60°F)
Working Pressure	34.5 N/sq cm	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	.71	2.87	6.47	11.50	17.98	25.89	35.24
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	2554.49	81.57	10.74	2.54	.83	.34	.15
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	2610.48	167.61	124.00	144.09	171.45	201.00	231.91
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	6.48	10.20	13.56	16.74	19.79	22.76	25.67
Insulation Tks(cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	574.54	17.93	2.34	.55	.21	.07	.07

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.048	0.193	0.435	0.773	1.208	1.740	2.368
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	175.436	5.482	0.722	0.171	0.056	0.023	0.010
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	179.199	11.204	8.333	9.684	11.522	13.508	15.585
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks(in)	0.747	0.980	1.142	1.266	1.367	1.452	1.524
ΔP/ft (lb/in^2)	833.3	26.0	3.4	0.8	0.3	0.1	0.1

TABLE D-3. - SYSTEM WEIGHTS -- LH_2 OMS AT LOWER FLOWRATE (CONCLUDED)

CASE

LIQUID HYDROGEN - OMS

Flowrate	2.5 kg/sec	(5.6 lb/sec)
No. of Line Fills		4
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft^{o}F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289K	(60^{o}F)
Working Pressure	34.5 N/sq cm	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	1.44	5.76	12.95	23.02	35.95	51.78	70.47
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	2610.49	81.57	10.74	2.54	.83	.34	.15
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	2667.20	170.50	130.46	155.61	189.42	226.88	267.14
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	6.48	10.20	13.56	16.74	19.79	22.76	25.67
Insulation Tks(cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	574.54	17.93	2.34	.55	.21	.07	.07

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.097	0.387	0.870	1.547	2.417	3.480	4.736
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	175.436	5.482	0.722	0.171	0.056	0.023	0.010
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	179.248	11.398	8.768	10.458	12.731	15.248	17.953
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks(in)	0.747	0.980	1.142	1.266	1.367	1.452	1.524
ΔP/ft (lb/in^2)	833.3	26.0	3.4	0.8	0.3	0.1	0.1

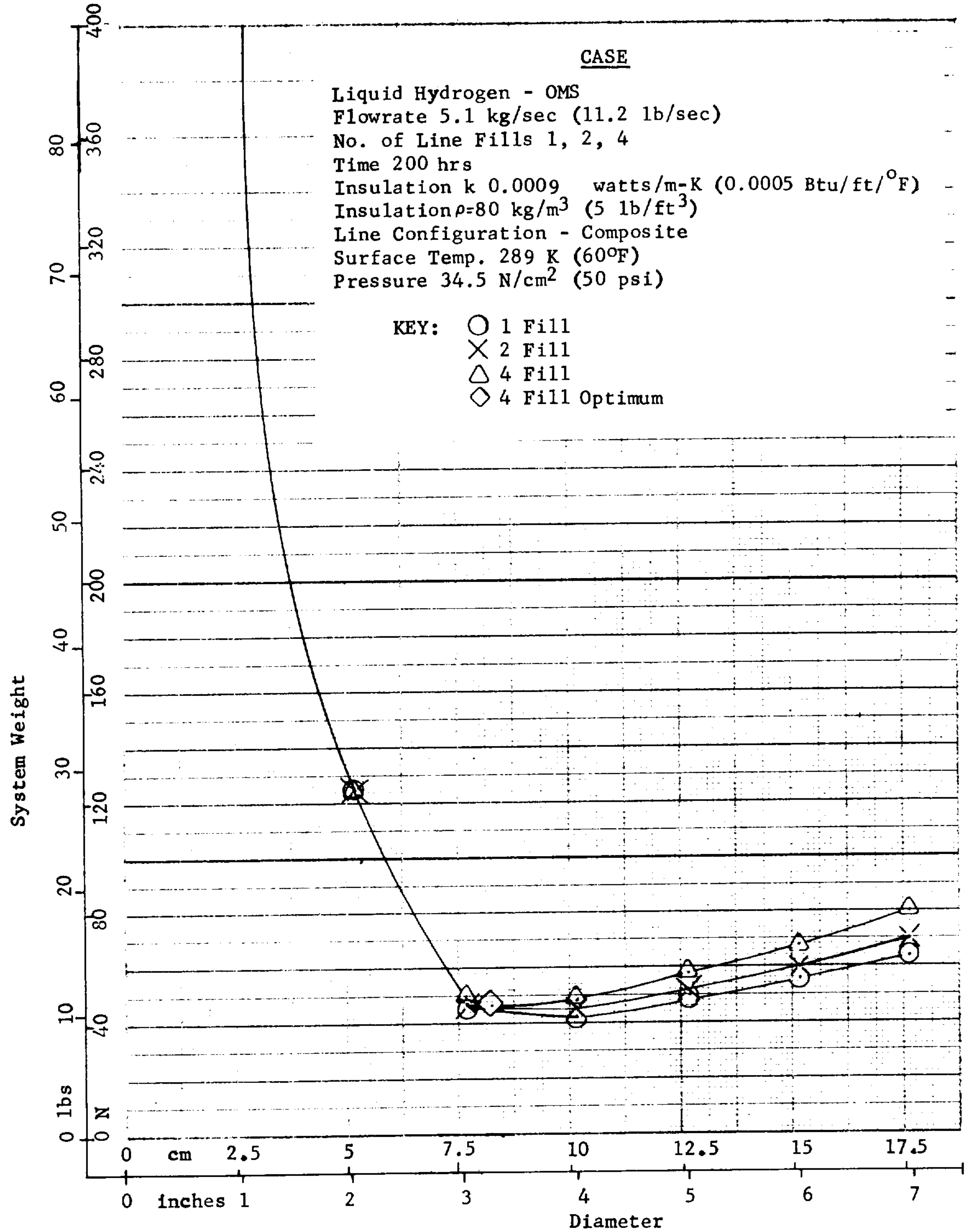


Figure D-25. - System Weight Optimization -- LH_2 OMS at High Flowrate

TABLE D-4. - SYSTEM WEIGHTS -- LH_2 OMS AT HIGH FLOWRATE

CASE

LIQUID HYDROGEN - OMS

Flowrate	5.1 kg/sec	(11.2 lb/sec)
No. of Line Fills		1
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	.36	1.44	3.23	5.76	8.99	12.96	17.62
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	10,422.	326.32	42.97	10.19	3.35	1.34	.62
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	10,497.60	410.03	152.98	146.00	164.98	189.06	214.76
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	6.48	10.20	13.56	16.74	19.79	22.76	25.67
Insulation Tks(cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	2298.17	71.84	9.45	2.28	.76	.28	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.024	0.097	0.217	0.387	0.604	0.870	1.184
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	701.745	21.930	2.888	0.685	0.225	0.090	0.042
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	705.484	27.556	10.281	9.812	11.087	12.705	14.433
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks(in)	0.747	0.980	1.142	1.266	1.367	1.452	1.525
ΔP/ft (lb/in^2)	3333.2	104.2	13.7	3.3	1.1	0.4	0.2

TABLE D-4. - SYSTEM WEIGHTS -- LH_2 OMS AT HIGH FLOWRATE (CONT.)

CASE

LIQUID HYDROGEN - OMS

Flowrate	5.1 kg/sec	(11.2 lb/sec)
No. of Line Fills		2
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	.71	2.87	6.47	11.50	17.98	25.89	35.24
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	10,442.	326.32	42.97	10.19	3.35	1.34	.62
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	10,497.99	412.36	156.21	151.74	173.97	202.00	232.38
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	6.48	10.20	13.56	16.74	19.79	22.76	25.67
Insulation Tks(cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	2298.17	71.84	9.45	2.28	.76	.28	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.048	0.193	0.435	0.773	1.208	1.740	2.368
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	701.745	21.930	2.888	0.685	0.225	0.090	0.042
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	705.508	27.652	10.498	10.198	11.691	13.575	15.617
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks(in)	0.747	0.980	1.142	1.266	1.367	1.452	1.525
ΔP/ft (lb/in^2)	3333.2	104.2	13.7	3.3	1.1	0.4	0.2

TABLE D-4. - SYSTEM WEIGHTS -- LH_2 OMS AT HIGH FLOWRATE (CONCLUDED)

CASE

LIQUID HYDROGEN - OMS

Flowrate	5.1 kg/sec	(11.2 lb/sec)
No. of Line Fills		4
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	1.44	5.76	12.96	23.02	35.96	51.78	70.47
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	10,442.	326.32	42.97	10.19	3.35	1.34	.62
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	10,498.70	415.25	162.70	163.26	191.95	227.88	267.61
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (cm)	6.48	10.20	13.56	16.74	19.79	22.76	25.67
Insulation Tks (cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	2298.17	71.84	9.45	2.28	.76	.28	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.097	0.387	0.870	1.547	2.417	3.480	4.736
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	701.745	21.930	2.888	0.685	0.225	0.090	0.042
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	705.557	27.846	10.934	10.972	12.900	15.315	17.985
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks (in)	0.747	0.980	1.142	1.266	1.367	1.452	1.525
ΔP/ft (lb/in^2)	3333.2	104.2	13.7	3.3	1.1	0.4	0.2

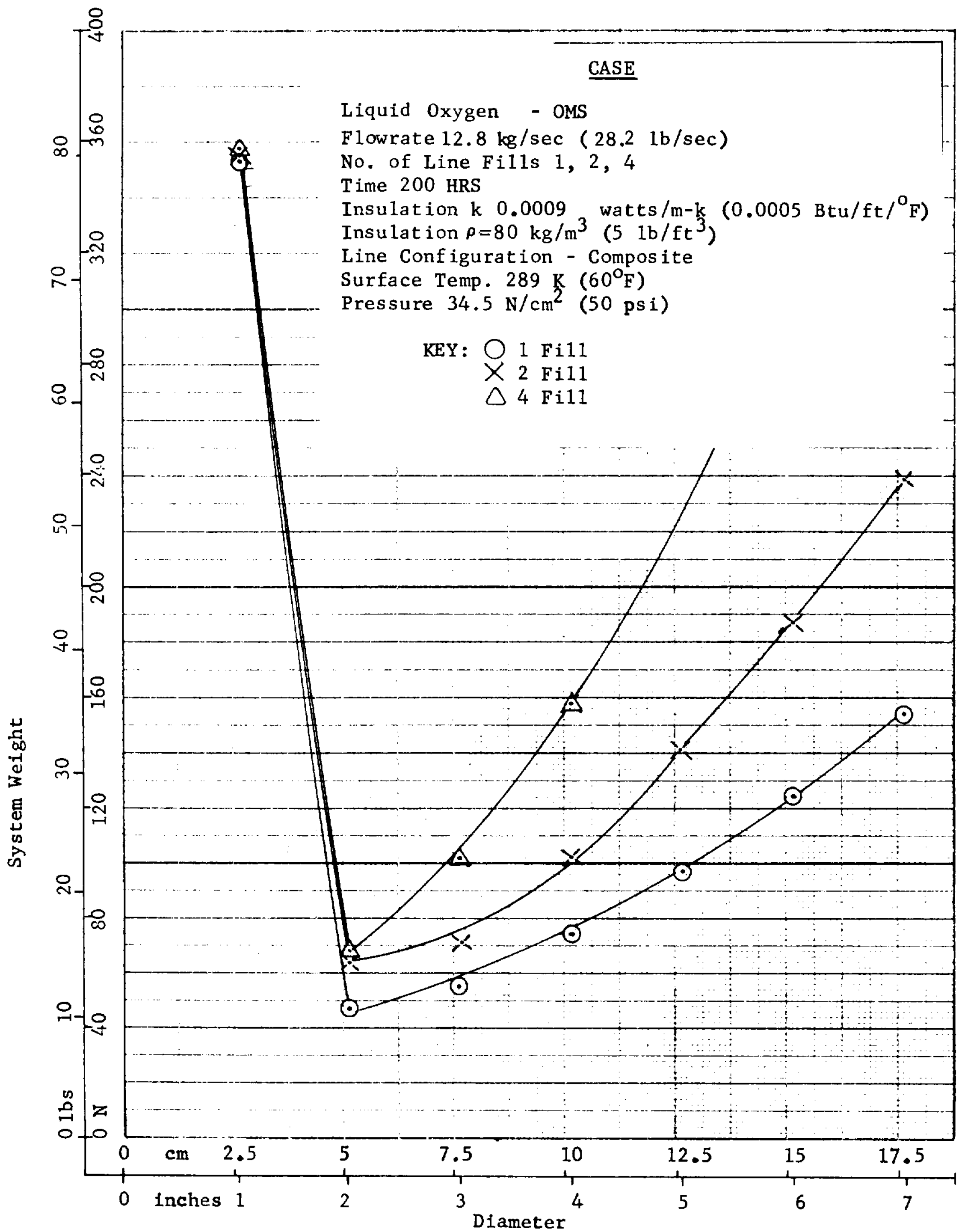


Figure D-26. - System Weight Optimization -- LOX OMS At Low Flowrate

TABLE D-5. - SYSTEM WEIGHTS -- LOX OMS AT LOWER FLOWRATE

CASE

LIQUID OXYGEN - OMS

Flowrate	12.8 kg/sec	(28.2 lb/sec)
No. of Line Fills		1
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	5.79	23.14	52.07	92.55	144.62	208.26	283.46
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	1098.64	34.33	4.52	1.07	.36	.13	.06
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	1173.39	158.56	184.79	248.32	325.16	413.51	513.13
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (cm)	7.41	11.38	14.92	18.24	21.40	24.47	27.46
Insulation Tks (cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	919.42	28.27	3.72	.90	.28	.14	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.389	1.555	3.499	6.220	9.719	13.996	19.050
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	73.833	2.307	0.304	0.072	0.024	0.009	0.004
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.700	5.514	6.304	7.075
TOTAL	78.856	10.596	12.419	16.688	21.852	27.790	34.484
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (in)	2.916	4.482	5.875	7.180	8.425	9.632	10.810
Insulation Tks (in)	0.930	1.213	1.410	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	1313.5	41.0	5.4	1.3	0.4	0.2	0.1

TABLE D-5. - SYSTEM WEIGHTS -- LOX OMS AT LOWER FLOWRATE (CONT.)

CASE

LIQUID OXYGEN - OMS

Flowrate	12.8 kg/sec	(28.2 lb/sec)
No. of Line Fills		2
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	11.58	46.28	104.13	185.12	289.25	416.52	566.92
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	1098.64	34.33	4.52	1.07	.36	.13	.06
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	1179.18	181.70	236.85	340.89	469.79	621.77	796.59
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (cm)	7.41	11.38	14.92	18.24	21.40	24.47	27.46
Insulation Tks (cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	919.42	28.27	3.72	.90	.28	.14	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.778	3.110	6.998	12.441	19.439	27.992	38.100
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	73.833	2.307	0.304	0.072	0.024	0.009	0.004
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.700	5.514	6.304	7.075
TOTAL	79.245	12.151	15.918	22.909	31.572	41.786	53.534
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (in)	2.916	4.482	5.875	7.180	8.425	9.632	10.810
Insulation Tks (in)	0.930	1.213	1.410	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	1313.5	41.0	5.4	1.3	0.4	0.2	0.1

TABLE D-5. - SYSTEM WEIGHTS -- LOX OMS AT LOWER FLOWRATE (CONCLUDED)

CASE

LIQUID OXYGEN - OMS

Flowrate	12.8 kg/sec	(28.2 lb/sec)
No. of Line Fills		4
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	23.14	92.55	208.26	370.24	578.50	833.04	1133.87
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	1098.64	34.33	4.52	1.07	.36	.13	.06
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	1190.74	227.97	340.98	526.00	759.04	1038.29	1363.54
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	7.41	11.38	14.92	18.24	21.40	24.47	27.46
Insulation Tks(cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	919.42	28.27	3.72	.90	.28	.14	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	1.555	6.220	13.996	24.882	38.878	55.984	76.201
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	73.833	2.307	0.304	0.072	0.024	0.009	0.004
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.700	5.514	6.304	7.075
TOTAL	80.021	15.261	22.916	35.350	51.011	69.778	91.635
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.916	4.482	5.875	7.180	8.425	9.632	10.810
Insulation Tks(in)	0.930	1.213	1.410	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	1313.5	41.0	5.4	1.3	0.4	0.2	0.1

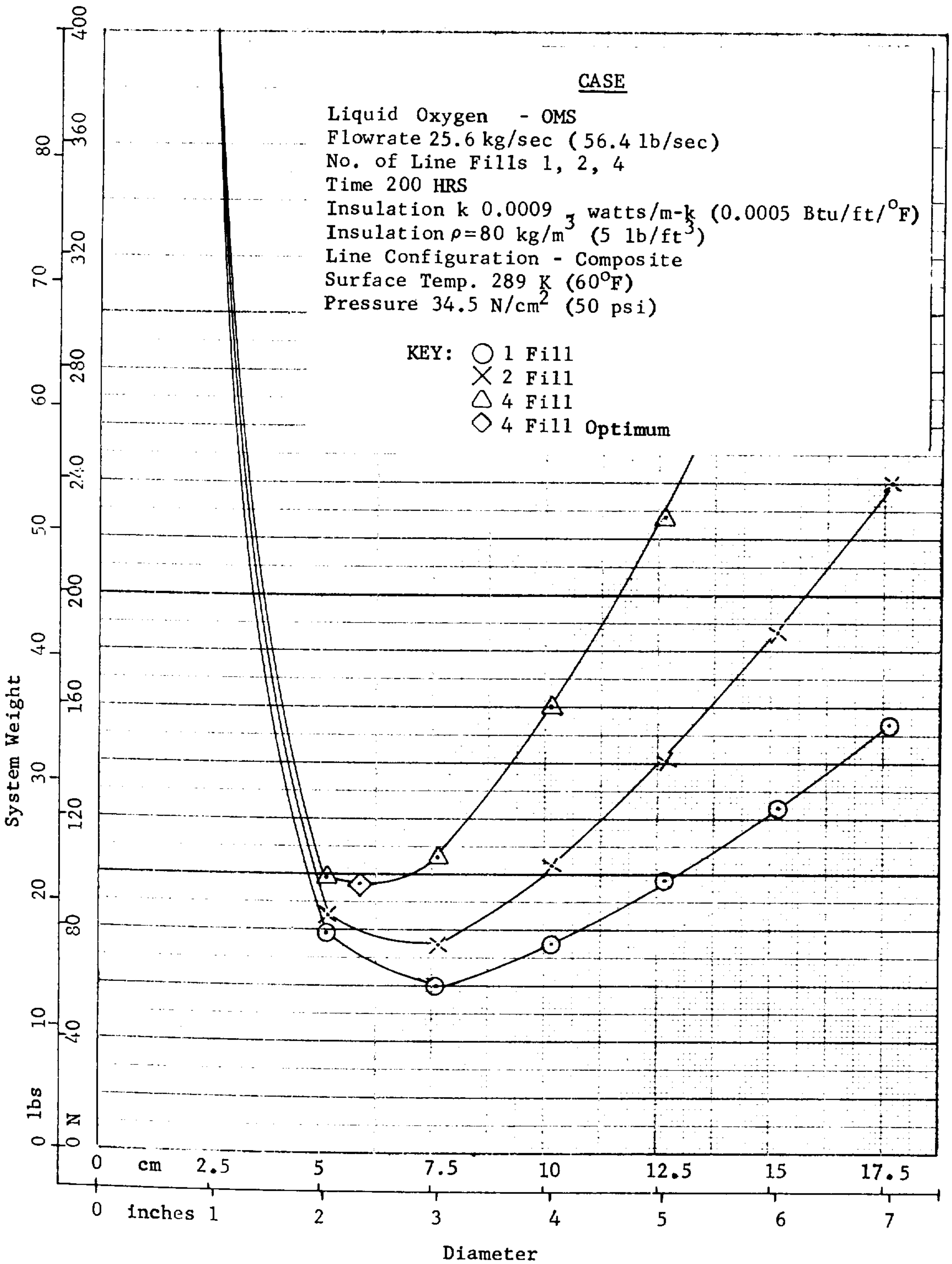


Figure D-27. - System Weight Optimization -- LOX OMS at High Flowrate

TABLE D-6. - SYSTEM WEIGHTS -- LOX OMS AT HIGH FLOWRATE

CASE

LIQUID OXYGEN - OMS

Flowrate	25.6 kg/sec	(56.4 lb/sec)
No. of Line Fills		1
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	5.79	23.14	52.07	92.55	144.62	208.26	283.46
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	4394.54	137.33	18.08	4.29	1.41	.57	.27
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	4469.29	261.56	198.35	251.54	326.21	413.95	513.34
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	7.41	11.38	14.92	18.24	21.40	24.47	27.46
Insulation Tks(cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	3622.53	1132.21	14.89	3.52	1.17	.48	.21

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.389	1.555	3.499	6.220	9.719	13.996	19.050
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	295.332	9.229	1.215	0.288	0.095	0.038	0.018
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.698	5.514	6.304	7.075
TOTAL	300.355	17.518	13.330	16.902	21.923	27.819	34.498
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.916	4.482	5.875	7.178	8.425	9.632	10.810
Insulation Tks(in)	0.930	1.213	1.409	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	5254.0	164.2	21.6	5.1	1.7	0.7	0.3

TABLE D-6. - SYSTEM WEIGHTS -- LOX OMS AT HIGH FLOWRATE (CONT.)

CASE

LIQUID OXYGEN - OMS

Flowrate	25.6 kg/sec	(56.4 lb/sec)
No. of Line Fills		2
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	11.58	46.28	104.13	185.12	289.25	416.52	566.93
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	4394.54	137.33	18.08	4.29	1.41	.57	.27
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	4475.08	284.70	250.41	344.11	470.84	622.21	796.81
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (cm)	7.41	11.38	14.92	18.23	21.40	29.47	27.46
Insulation Tks (cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	3622.53	1132.21	14.89	3.52	1.17	.48	.21

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	.778	3.110	6.998	12.441	19.439	27.992	38.100
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	295.332	9.229	1.215	0.288	0.095	0.038	0.018
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.698	5.514	6.304	7.075
TOTAL	300.744	19.073	16.829	23.123	31.643	41.815	53.548
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (in)	2.916	4.482	5.875	7.178	8.425	9.632	10.810
Insulation Tks (in)	0.930	1.213	1.409	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	5254.0	164.2	21.6	5.1	1.7	0.7	0.3

TABLE D-6. - SYSTEM WEIGHTS -- LOX OMS AT HIGH FLOWRATE (CONCLUDED)

CASE

LIQUID OXYGEN - OMS

Flowrate	25.6 kg/sec	(56.4 lb/sec)
No. of Line Fills		4
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	23.14	92.55	208.26	370.24	578.50	833.04	1133.87
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	4394.54	137.33	18.08	4.29	1.41	.57	.27
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	4486.64	330.97	354.54	529.23	760.09	1038.73	1363.75
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	7.41	11.38	14.92	18.24	21.40	24.47	27.46
Insulation Tks(cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	3622.53	1132.21	14.89	3.52	1.17	.48	.21

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	1.555	6.220	13.996	24.882	38.878	55.984	76.201
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	295.332	9.229	1.215	0.288	0.095	0.038	0.018
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.698	5.514	6.304	7.075
TOTAL	301.521	22.183	23.827	35.564	51.082	69.807	91.649
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.916	4.482	5.875	7.178	8.425	9.632	10.810
Insulation Tks(in)	0.930	1.213	1.409	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	5254.0	164.2	21.6	5.1	1.7	0.7	0.3

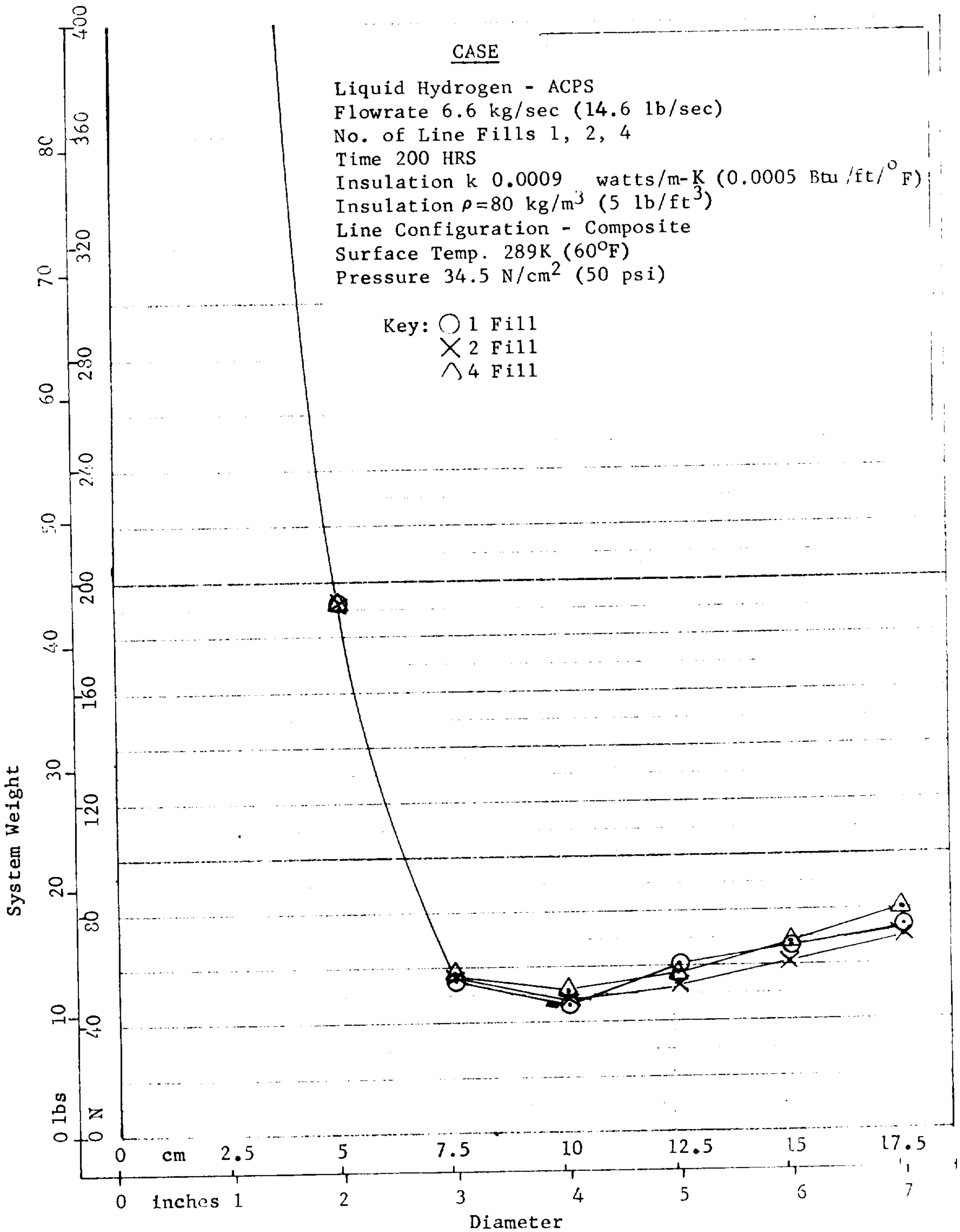


Figure D-28. - System Weight Optimization -- LH_2 ACPS

TABLE D-7. - SYSTEM WEIGHTS -- LH_2 ACPS

CASE

LIQUID HYDROGEN - ACPS

Flowrate	6.6 kg/sec	(14.6 lb/sec)
No. of Line Fills		1
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft^{o}F)
Insulation ρ	80 kg/m^3	5.0 lb/ft^3
Fuel Line Configuration		Composite Line
Surface Temperature	289K	(60^{o}F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	.36	1.44	3.23	5.76	8.99	12.95	17.62
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	17,744.	554.50	73.02	17.34	5.68	2.28	1.06
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	17,800	639.11	183.02	153.15	167.31	189.99	215.20
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (cm)	6.47	10.20	13.56	16.74	19.79	22.75	25.67
Insulation Tks (cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	3905.21	122.03	16.06	3.79	1.24	.48	.21

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.452	0.565	0.678	0.790
Line Fill	0.024	0.097	0.217	0.387	0.604	0.870	1.184
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	1192.475	37.265	4.907	1.165	0.382	0.153	0.071
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	1196.214	42.891	12.300	10.291	11.244	12.768	14.462
CORRESPONDING DIMENSIONS							
Vac Jacket Dia (in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks (in)	0.747	0.980	1.142	1.266	1.367	1.452	1.525
ΔP/ft (lb/in^2)	5664.0	177.0	23.3	5.5	1.8	0.7	0.3

TABLE D-7. - SYSTEM WEIGHTS -- LH_2 ACPS (CONT.)

CASE

LIQUID HYDROGEN - ACPS

Flowrate	6.6 kg/sec	(14.6 lb/sec)
No. of Line Fills		2
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft^{o}F)
Insulation ρ	80 kg/m^3	5.0 lb/ft^3
Fuel Line Configuration		Composite Line
Surface Temperature	289K	(60^{o}F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	.71	2.87	6.47	11.50	17.98	25.89	35.24
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	17,744.	554.50	73.02	17.34	5.68	2.28	1.06
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24.83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	17,800	640.54	186.26	158.89	176.30	202.93	232.82
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	6.47	10.20	13.56	16.74	19.79	22.75	25.67
Insulation Tks(cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g cm^2)	3905.21	122.03	16.06	3.79	1.24	.48	.21

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.048	0.193	0.435	0.773	1.208	1.740	2.368
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	1192.475	37.265	4.907	1.165	0.382	0.153	0.071
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	1196.238	42.987	12.518	10.678	11.848	13.638	15.646
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks(in)	0.747	0.980	1.142	1.266	1.367	1.452	1.525
ΔP/ft (lb/in^2)	5664.0	177.0	23.3	5.5	1.8	0.7	0.3

TABLE D-7. - SYSTEM WEIGHTS -- LH_2 ACPS (CONCLUDED)

CASE

LIQUID HYDROGEN - ACPS

Flowrate	6.6 kg/sec	(14.6 lb/sec)
No. of Line Fills		4
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	1.44	5.76	12.95	23.02	35.96	51.78	70.47
Boil Off	26.53	34.94	41.92	48.21	54.10	59.71	65.11
Pressure System	17,744.	554.50	73.02	17.34	5.68	2.28	1.06
Insulation	2.19	4.84	7.78	10.94	14.26	17.69	21.23
Vacuum Jacket	24 83	39.10	52.00	64.16	75.87	87.27	98.42
TOTAL	17,800	643.43	192.74	170.41	194.28	228.82	268.05
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	6.47	10.20	13.56	16.74	19.79	22.75	25.67
Insulation Tks(cm)	1.90	2.49	2.90	3.22	3.47	3.69	3.87
ΔP/cm (g/cm^2)	3905.21	122.03	16.06	3.79	1.24	.48	.21

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.097	0.387	0.870	1.547	2.417	3.480	4.736
Boil Off	1.783	2.348	2.817	3.240	3.636	4.013	4.376
Pressure System	1192.475	37.265	4.907	1.165	0.382	0.153	0.071
Insulation	0.147	0.325	0.523	0.735	0.958	1.189	1.427
Vacuum Jacket	1.669	2.628	3.495	4.312	5.099	5.865	6.614
TOTAL	1196.287	43.181	12.953	11.452	13.057	15.378	18.014
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.550	4.016	5.339	6.589	7.791	8.961	10.106
Insulation Tks(in)	0.747	0.980	1.142	1.266	1.367	1.452	1.525
ΔP/ft (lb/in^2)	5664.0	177.0	23.3	5.5	1.8	0.7	0.3

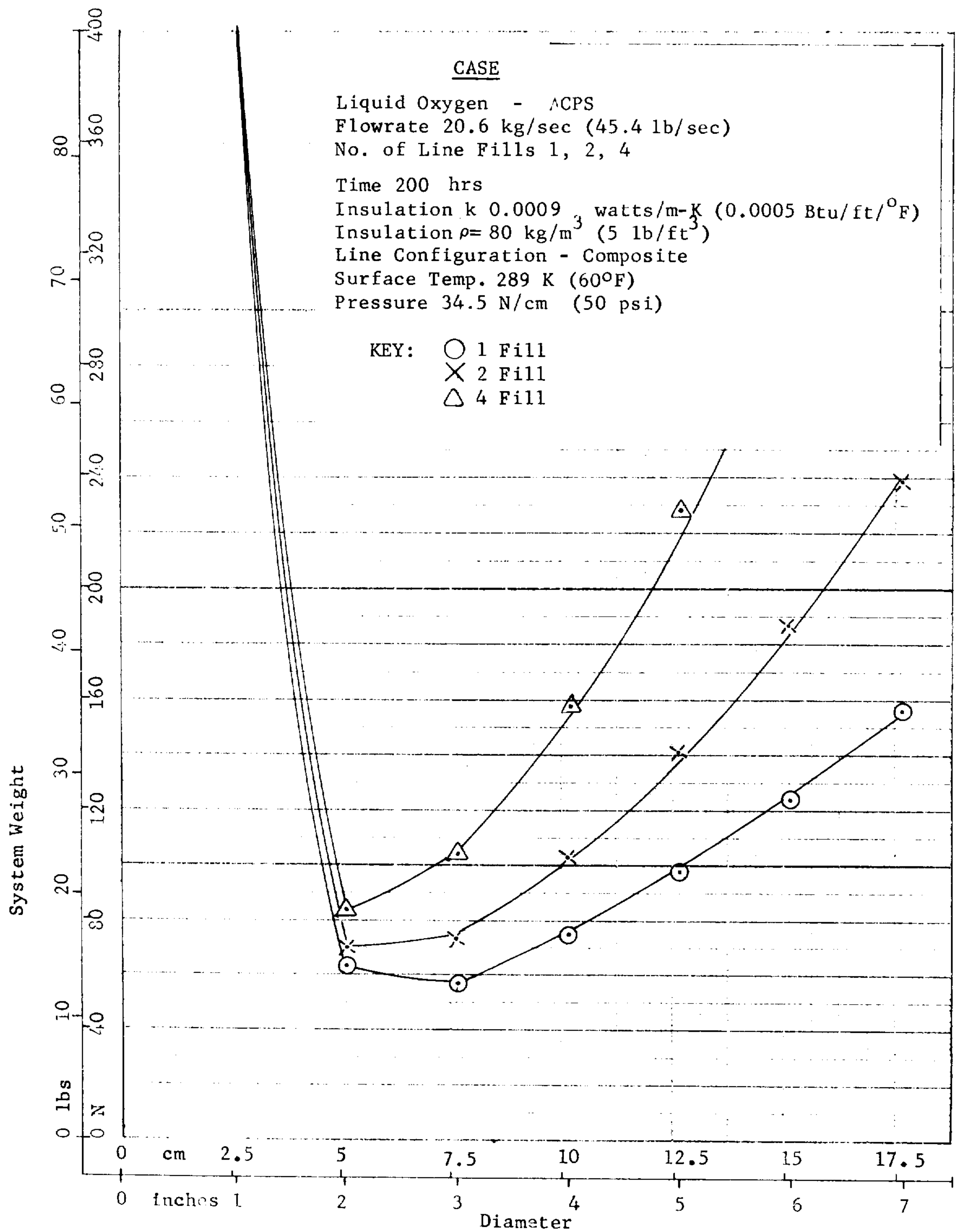


Figure D-29. - System Weight Optimization -- LOX ACPS

TABLE D-8. - SYSTEM WEIGHTS -- LOX ACPS

CASE

LIQUID OXYGEN - ACPS

Flowrate	20.6 kg/sec	(45.4 lb/sec)
No. of Line Fills		1
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft^{o}F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60^{o}F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	5.79	23.14	52.07	92.55	144.62	208.26	283.46
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	2847.51	88.98	11.73	2.78	.91	.37	.16
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	2922.26	213.21	192.00	250.03	325.71	413.75	513.23
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	7.41	11.38	14.92	18.23	21.40	24.46	27.46
Insulation Tks(cm)	2.36	3.08	3.58	3.96	4.28	4.54	9.77
ΔP/cm (g/cm^2)	2347.20	73.36	9.65	2.30	.76	.28	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.389	1.555	3.499	6.220	9.719	13.996	19.050
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	191.365	5.980	0.788	0.187	0.061	0.025	0.011
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.698	5.514	6.304	7.075
TOTAL	196.388	14.269	12.903	16.801	21.889	27.806	34.491
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.916	4.482	5.875	7.178	8.425	9.632	10.810
Insulation Tks(in)	0.930	1.213	1.410	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	3404.3	106.4	14.0	3.3	1.1	0.4	0.2

TABLE D-8. - SYSTEM WEIGHTS -- LOX ACPS (CONT.)

CASE

LIQUID OXYGEN - ACPS

Flowrate	20.6 kg/sec	(45.4 lb/sec)
No. of Line Fills		2
Time of Mission		200 hrs.
Insulation k	0.0009 watts/m-K	(0.0005 Btu/ft^{o}F)
Insulation ρ	80 kg/m^3	(5.0 lb/ft^3)
Fuel Line Configuration		Composite Line
Surface Temperature	289K	(60^{o}F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	11.58	46.28	104.13	185.12	289.25	416.52	566.93
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	2847.51	88.98	11.73	2.78	.91	.37	.16
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.91	82.05	93.80	105.28
TOTAL	2928.05	236.35	244.06	342.57	470.34	622.01	796.70
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	7.41	11.38	14.92	18.23	21.40	24.46	27.46
Insulation Tks(cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	2347.20	73.36	9.65	2.30	.76	.28	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	0.778	3.110	6.998	12.441	19.439	27.992	38.100
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	191.365	5.980	0.788	0.187	0.061	0.025	0.011
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.698	5.514	6.304	7.075
TOTAL	196.777	15.824	16.402	23.022	31.609	41.802	53.541
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.916	4.482	5.875	7.178	8.425	9.632	10.810
Insulation Tks(in)	0.930	1.213	1.410	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	3404.3	106.4	14.0	3.3	1.1	0.4	0.2

TABLE D-8. - SYSTEM WEIGHTS -- LOX ACPS (CONCLUDED)

CASE

LIQUID OXYGEN - ACPS

Flowrate	20.6 kg/sec	(45.4 lb/sec)
No. of Line Fills		4
Time of Mission		200 hrs.
Insulation k	0.0009 Watts/m-K	(0.0005 Btu/ft°F)
Insulation ρ	80 kg/m^3	5.0 lb/ft^3
Fuel Line Configuration		Composite Line
Surface Temperature	289 K	(60°F)
Working Pressure	34.5 N/cm^2	(50 psi)

COMPONENT WEIGHT (g/cm)

COMPONENT	INNER LINE DIAMETER (cm)						
	2.54	5.08	7.62	10.16	12.70	15.24	17.78
Inner Line	1.73	4.29	5.07	6.74	8.41	10.09	11.76
Line Fill	23.14	92.55	208.26	370.24	578.50	833.04	1133.87
Boil Off	35.85	46.72	55.70	63.78	71.30	78.46	85.35
Pressure System	2847.51	88.98	11.73	2.78	.91	.37	.16
Insulation	2.99	6.44	10.22	14.24	18.42	22.77	27.22
Vacuum Jacket	28.39	43.64	57.21	69.94	82.05	93.80	105.28
TOTAL	2928.05	236.35	244.06	342.57	470.34	622.01	796.70
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(cm)	7.41	11.38	14.92	18.23	21.40	24.46	27.46
Insulation Tks(cm)	2.36	3.08	3.58	3.96	4.28	4.54	4.77
ΔP/cm (g/cm^2)	2347.20	73.36	9.65	2.30	.76	.28	.14

COMPONENT WEIGHT (LB/FT)

	INNER LINE DIAMETER (INCHES)						
	1	2	3	4	5	6	7
Inner Line	0.116	0.228	0.341	0.453	0.565	0.678	0.790
Line Fill	1.555	6.220	13.996	24.882	38.878	55.924	76.201
Boil Off	2.409	3.140	3.743	4.286	4.792	5.273	5.736
Pressure System	191.365	5.980	0.788	0.187	0.061	0.025	0.011
Insulation	0.201	0.433	0.687	0.957	1.238	1.530	1.829
Vacuum Jacket	1.908	2.933	3.845	4.698	4.514	6.304	7.075
TOTAL	197.554	18.934	23.400	35.463	51.049	69.794	91.642
CORRESPONDING DIMENSIONS							
Vac Jacket Dia(in)	2.916	4.482	5.875	7.178	8.425	9.632	10.810
Insulation Tks(in)	0.930	1.213	1.410	1.561	1.684	1.788	1.877
ΔP/ft (lb/in^2)	3404.3	106.4	14.0	3.3	1.1	0.4	0.2

APPENDIX E

WEIGHT ANALYSIS

<u>APPENDIX E</u>

WEIGHT ANALYSIS

An analysis was performed to determine the weight savings that may be obtained if the all-metal propellant feedlines in the Phase B configuration of the Space Shuttle vehicle were replaced with composite feedlines. The results of this analysis are tabulated in Table E-1.

The weight of the all-metal lines was based on data contained in the mass properties reports (references 3 and 5) from the Phase B studies. The weight of the corresponding composite lines was determined by the WEATOPT computer program which optimizes the tube weight as a function of the operating pressure and thermal contraction of the feedline at operating temperature. The section code used in column 2 of the table refers to the descriptive code indicated on the line drawings of the candidate systems which are included in Appendix B of this report. The results of the analysis show that the maximum weight savings are achieved with an all-welded assembly where the flanged connections are replaced with buttwelded joints. Line assembly and installation techniques must be evaluated to determine if this method is practical.

The Phase B design used aluminum and stainless steel conoseal flanges extensively in the assembly of the propellant systems. Since the optimum weight composite lines use Inconel or 21-6-9 steel as the liner material, the weight savings using stainless steel flanges are shown on the rows of the table designated with a △. The second set of data in the table (▽) shows the weight savings possible if an all-welded configuration can be used. The third data type in the table (◇) indicates the weight savings that may be realized if aluminum flanges can be explosively bonded to the Inconel or stainless steel liners. Where the Phase B designed systems use buttweld joints, the table indicates buttweld joints (◊) for the composite lines. The weight savings from using 21-6-9, 304L stainless steel or aluminum as the liner material is also shown for typical feedline sections.

TABLE E-1. - WEIGHT SAVINGS OBTAINABLE BY USE OF COMPOSITE LINES IN THE SPACE SHUTTLE VEHICLE

DESCRIPTION	SECTION CODE	DIAMETER	LENGTH	PHASE B CONFIGURATION				COMPOSITE CONFIGURATION						WEIGHT SAVINGS/ SECTION kg (lbs)	NO. OF SECTIONS	TOTAL WEIGHT SAVINGS kg (lbs)
				MATERIAL	WALL THICKNESS cm (in.)	END FITTINGS	SECTION TOTAL WT. kg (lbs)	END FITTING CODE	LINER MATERIAL	LINER THICKNESS cm (in.)	END FITTINGS	END FITTING TOTAL WT. kg (lbs)	SECTION TOTAL WT. kg (lbs)			
Booster Main Engine LOX Feedline	3	56 (22)	305 (120)	2219-T87AL	0.203 (0.080)	Conoseal-Al	34 (75)	△	Inconel	0.0165 (0.0065)	Conoseal-SS Buttweld Transi-tion SS	10 (22) 1.13 (2.5)	26 (58)	8 (17)	2	16 (34)
	"	"	"	"	"	"	"	"	21-6-9	0.0165 (0.0065)	" "	"	26 (58)	8 (17)	2	16 (34)
	"	"	"	"	"	"	"	"	304L	0.0480 (0.0189)	" "	"	40 (87)	-5 (-12)		
	"	"	"	"	"	"	"	"	Aluminum	0.0655 (0.0258)	Conoseal-Al Buttweld Transi-tion Al	3.41 (7.5) 1.71 (3.74)	23 (50)	11 (25)	2	22 (50)
	"	"	"	"	"	"	"	◇	Inconel	0.0165 (0.0065)	Conoseal-Al Buttweld Transi-tion Al	3.41 (7.5) 1.7 (3.74)	20 (44)	14 (31)	2	28 (62)
	"	"	"	"	"	"	"	▽	Inconel	0.0165 (0.0065)	Buttweld Transi-tion SS	2.26 (5)	18 (39)	16 (36)	2	32 (72)
	4a	56 (22)	610 (240)	2219-T87AL	0.203 (0.080)	Conoseal-Al	68 (150)	△	Inconel	0.0188 (0.0074)	Conoseal SS	20 (44)	53 (116)	15 (34)	2	30 (68)
	"	"	"	"	"	"	"	▽	Inconel	0.0188 (0.0074)	Buttweld Transi-tion SS	2.26 (5)	35 (77)	33 (73)	2	66 (146)
	4b	56 (22)	610 (240)	2219-T87AL	0.203 (0.080)	Conoseal-Al	68 (150)	△	Inconel	0.0218 (0.0086)	Conoseal SS	20 (44)	55 (121)	13 (29)	2	26 (58)
	"	"	"	"	"	"	"	▽	Inconel	0.0218 (0.0086)	Buttweld Transi-tion	2.26 (5)	37 (82)	31 (68)	2	62 (136)
	4c	56 (22)	610 (240)	2219-T87AL	0.213 (0.084)	Conoseal-Al	71 (157)	△	Inconel	0.0259 (0.0102)	Conoseal SS	20 (44)	58 (129)	13 (28)	2	26 (56)

NOTES:
1. The section code in column 2 refers to the layout drawing of the line indicated in column 1 and shown schematically in Appendix B.
2. Phase B configuration refers to the MDAC/MMC design as of 1 July 1971.
3. The thickness of the buttweld transitions for the composite lines is equal to or greater than the thickness of the Phase B lines.

TABLE E-1. - WEIGHT SAVINGS OBTAINABLE BY USE OF COMPOSITE LINES IN THE SPACE SHUTTLE VEHICLE (Continued)

DESCRIPTION	SECTION CODE	DIAMETER	LENGTH	PHASE B CONFIGURATION				COMPOSITE CONFIGURATION						WEIGHT SAVINGS/ SECTION kg (lbs)	NO. OF SECTIONS	TOTAL WEIGHT SAVINGS kg (lbs)
				MATERIAL	WALL THICKNESS cm (in.)	END FITTINGS	SECTION TOTAL WT. kg (lbs)	END FITTING CODE	LINER MATERIAL	LINER THICKNESS cm (in.)	END FITTINGS	END FITTING TOTAL WT. kg (lbs)	SECTION TOTAL WT. kg (lbs)			
Booster Main Engine LOX Feedline	4c	56 (22)	610 (240)	2219-T87 Al	0.213 (0.084)	Conoseal Al	71 (157)	▽	Inconel	0.0259 (0.0102)	Buttweld Transition SS	2.26 (5)	41 (90)	30 (67)	2	60 (132)
	4d	56 (22)	610 (240)	" "	0.239 (0.094)	" "	72 (159)	△	" "	0.0300 (0.0118)	Conoseal SS	20 (44)	63 (138)	9 (21)	2	18 (42)
	" "	" "	" "	" "	" "	" "	" "	▽	" "	0.0300 (0.0118)	Buttweld Transition SS	2.26 (5)	45 (99)	27 (60)	2	54 (120)
	5	56 (22)	610 (240)	" "	0.264 (0.104)	Conoseal Al Conoseal SS	93 (205)	△	" "	0.0340 (0.0134)	Conoseal SS	20 (44)	66 (145)	27 (60)	2	54 (120)
	" "	" "	" "	" "	" "	" "	" "	▽	" "	0.0340 (0.0134)	Buttweld Transition SS	2.26 (5)	48 (106)	45 (99)	2	90 (198)
Booster Main Engine LOX Manifold	6a	56 (22)	152 (60)	21-6-9 SS	0.318 (0.125)	Buttweld	67 (148)	◊	" "	0.0445 (0.0175)	Buttweld Transition SS	2.26 (5)	18 (40)	49 (108)	2	98 (216)
	6b	56 (22)	152 (60)	" "	0.318 (0.125)	Buttweld	67 (148)	◊	" "	0.0445 (0.0175)	Buttweld Transition SS	2.26 (5)	18 (40)	49 (108)	2	98 (216)
	8a	20 (8)	330 (130)	" "	0.114 (0.045)	Buttweld	20 (43)	◊	" "	0.0147 (0.0058)	Buttweld Transition SS	.59 (1.3)	6 (14)	14 (29)	1	14 (29)
Booster Main Engine LOX Feed Ducts	4a Eng. 1&4	31 (12)	132 (52)	" "	0.160 (0.063)	Conoseal SS Buttweld	21 (47)	△	" "	0.0213 (0.0084)	Conoseal SS Buttweld Transition SS	5.44 (12) .62 (1.36)	10 (22)	11 (25)	2	22 (50)
	4a Eng. 2&3	31 (12)	102 (40)	" "	0.160 (0.063)	Conoseal SS Buttweld	18 (39)	△	" "	0.0213 (0.0084)	" "	5.44 (12) .62 (1.36)	9 (20)	9 (19)	2	18 (38)
	1&2 or 6&7	38 (15)	185 (73)	" "	0.203 (0.080)	Conoseal SS Buttweld	43 (94)	△	" "	0.0290 (0.0114)	Conoseal SS Buttweld Transition SS	6.80 (15) .98 (2.16)	16 (36)	27 (58)	12	324 (696)

TABLE E-1. - WEIGHT SAVINGS OBTAINABLE BY USE OF COMPOSITE LINES IN THE SPACE SHUTTLE VEHICLE (Continued)

DESCRIPTION	SECTION CODE	DIAMETER cm (in.)	LENGTH	PHASE B CONFIGURATION MATERIAL	PHASE B CONFIGURATION WALL THICKNESS cm (in.)	PHASE B CONFIGURATION END FITTING	PHASE B CONFIGURATION SECTION TOTAL WT. kg (lbs)	COMPOSITE CONFIGURATION END FITTING CODE	COMPOSITE CONFIGURATION LINER MATERIAL	COMPOSITE CONFIGURATION LINER THICKNESS cm (in.)	COMPOSITE CONFIGURATION END FITTING	COMPOSITE CONFIGURATION END FITTING TOTAL WT. kg (lbs)	COMPOSITE CONFIGURATION SECTION TOTAL WT. kg (lbs)	WEIGHT SAVINGS/ SECTION kg (lbs)	NO. OF SECTIONS	TOTAL WEIGHT SAVINGS kg (lbs)
Booster Main Engine LOX Fill & Drain	1& 2a	25 (10)	310 (122)	21-6-9 SS	0.089 (0.035)	Buttweld	18 (40)	◇	Inconel	0.0180 (0.0071)	Buttweld Transition SS	.57 (1.26)	9 (20)	9 (20)	1	9 (20)
	3a	25 (10)	91 (36)	" "	0.089 (0.035)	Buttweld	5 (11)	◇	Inconel	0.0180 (0.0071)	" "	.57 (1.26)	2.7 (6)	2.3 (5)	1	2.3 (5)
Booster Main Engine LH_2 Feed Ducts	1 Eng. 2&3	31 (12)	94 (37)	" "	0.091 (0.036)	Conoseal SS Buttweld	12 (26)	△	Inconel	0.0076 (0.0030)	Conoseal SS Buttweld Transition SS	5.44 (12) .35 (0.78)	8 (17)	4 (9)	2	8 (18)
	1 Eng. 5&8	31 (12)	145 (57)	" "	0.091 (0.036)	" "	15 (34)	△	Inconel	0.0076 (0.0030)	" "	5.44 (12) .35 (0.78)	9 (19)	6 (15)	2	12 (30)
	1 Eng. 10 & 11	31 (12)	81 (32)	" "	0.091 (0.036)	" "	11 (24)	△	Inconel	0.0076 (0.0030)	" "	5.44 (12) .35 (0.78)	7 (16)	4 (8)	2	8 (16)
	3&4	38 (15)	145 (57)	" "	0.102 (0.040)	" "	21 (46)	△	Inconel	0.0076 (0.0030)	" "	6.80 (15) .49 (1.08)	11 (24)	10 (22)	6	60 (132)
	6 Eng. 6&7	38 (15	102 (40)	" "	0.102 (0.040	" "	17 (37)	△	Inconel	0.0076 (0.0030)	" "	6.80 (15) .49 (1.08)	10 (22)	7 (15)	2	14 (30)
	11 Eng 1&4	31 (12)	114 (45)	" "	0.091 (0.036)	" "	14 (30)	△	Inconel	0.0076 (0.0030)	" "	5.44 (12) .35 (0.78)	8 (18)	6 (12)	2	12 (24)
	11 Eng. 9&12	31 (12)	89 (35)	" "	0.091 (0.036)	" "	12 (26)	△	Inconel	0.0076 (0.0030)	" "	5.44 (12) .35 (0.78)	8 (17)	4 (9)	2	8 (18)
	14 & 15	38 (15)	185 (73)	" "	0.102 (0.040)	" "	25 (54)	△	Inconel	0.0076 (0.0030	" "	6.80 (15) .49 (1.08)	12 (26)	13 (28)	4	52 (114)

TABLE E-1. - WEIGHT SAVINGS OBTAINABLE BY USE OF COMPOSITE LINES IN THE SPACE SHUTTLE VEHICLE (Continued)

				PHASE B CONFIGURATION				COMPOSITE CONFIGURATION								
DESCRIPTION	SECTION CODE	DIAMETER cm (in.)	LENGTH cm (in.)	MATERIAL	WALL THICKNESS cm (in.)	END FITTING	SECTION TOTAL WT. kg (lbs)	END FITTING CODE	LINER MATERIAL	LINER THICKNESS cm (in.)	END FITTING	END FITTING TOTAL WT. kg (lbs)	SECTION TOTAL WT. kg (lbs)	WEIGHT SAVINGS/ SECTION kg (lbs)	NO. OF SECTIONS	TOTAL WEIGHT SAVINGS kg (lbs)
Booster LH_2 Fill & Drain	1	25 (10)	305 (120)	21-6-9	0.081 (0.032)	Buttweld	16 (35)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	.62 (1.36)	6 (13)	10 (22)	1	10 (22)
	"	"	"	" "	" "	" "	"	"	Aluminum	0.0163 (0.0064)	Buttweld Transition SS	.62 (1.36)	5.44 (12)	10.56 (23)	1	10.56 (23)
	"	"	"	" "	" "	" "	"	"	21-6-9	0.0076 (0.0030)	" "	.62 (1.36)	6 (13)	10 (22)	1	10 (22)
	3a	25 (10)	91 (36)	21-6-9	0.081 (0.032)	Buttweld	5 (10)	◊	Inconel	0.0076 (0.0030)	" "	.62 (1.36)	2.27 (5)	2.73 (5)	1	2.73 (5)
	4a	25 (10)	203 (80)	" "	0.081 (0.032)	Buttweld	10 (23)	◊	Inconel	0.0076 (0.0030)	" "	.62 (1.36)	4 (9)	6 (14)	1 1	6 (14)
Orbiter Main Engine LOX Feedline	1a	46 (18)	808 (318)	Aluminum	0.127 (0.050)	Conoseal Al Conoseal SS	53 (116)	△	Inconel	0.0150 (0.0060)	Conoseal SS	16 (35)	48 (105)	5 (11)	2	10 (22)
	"	"	"	" "	" "	" "	"	△	Inconel	0.0150 (0.0060)	Conoseal SS Buttweld Transition SS	7.84 (17.3) .73 (1.62)	40 (89)	13 (27)	2	26 (54)
	"	"	"	" "	" "	" "	"	◇	Inconel	0.0150 (0.0060)	Conoseal Al Buttweld Transition Al	3.08 (6.8) 1.10 (2.43)	36 (79)	17 (37)	1	17 (37)
	2	46 (18)	808 (318)	Aluminum	0.127 (0.050)	Conoseal Al	48 (105)	◇	Inconel	0.0165 (0.0065)	" "	3.08 (6.8) 1.10 (2.43)	37 (81)	11 (24)	2	22 (48)
	"	"	"	" "	" "	" "	"	▽	Inconel	0.0165 (0.0065)	Buttweld Transition SS	1.47 (3.24)	35 (76)	13 (29)	2	26 (58)
	3a	46 (18)	478 (188)	Aluminum	0.127 (0.050)	Conoseal Al	28 (61)	◇	Inconel	0.0170 (0.0067)	Conoseal Al Al Buttweld Transition	3.08 (6.8) 1.10 (2.43)	24 (53)	4 (8)	1	4 (8)

TABLE E-1. - WEIGHT SAVINGS OBTAINABLE BY USE OF COMPOSITE LINES IN THE SPACE SHUTTLE VEHICLE (Continued)

DESCRIPTION	SECTION CODE	DIAMETER cm (in.)	LENGTH cm (in.)	PHASE B CONFIGURATION				COMPOSITE CONFIGURATION						WEIGHT SAVINGS/ SECTION kg (lbs)	NO. OF SECTIONS	TOTAL WEIGHT SAVINGS kg (lbs)
				MATERIAL	WALL THICKNESS cm (in.)	END FITTING	SECTION TOTAL WT. kg (lbs)	END FITTING CODE	LINER MATERIAL	LINER THICKNESS cm (in.)	END FITTING	END FITTING TOTAL WT. kg (lbs)	SECTION TOTAL WT. kg (lbs)			
Orbiter Main Engine LOX Feedline	3a	46 (18)	478 (188)	Aluminum	0.127 (0.050)	Conoseal Al	28 (61)	▽	Inconel	0.0170 (0.0067)	Buttweld Transition SS	1.10 (2.43) .73 (1.62)	22 (48)	6 (13)	1	6 (13)
	5a	46 (18)	229 (90)	21-6-9	0.127 (0.050)	Buttweld	33 (73)	◊	Inconel	0.0180 (0.0071)	Buttweld Transition SS	1.47 (3.24)	11 (25)	22 (48)	1	22 (48)
	6	46 (18)	508 (200)	Aluminum	0.127 (0.050)	Conoseal Al	32 (71)	▽	Inconel	0.0173 (0.0068)	Buttweld Transition SS	1.47 (3.24)	23 (50)	9 (21)	1	9 (21)
	7a	46 (18)	132 (52)	21-6-9	0.127 (0.050)	Buttweld	19 (42)	◊	Inconel	0.0178 (0.0070)	Buttweld Transition SS	1.47 (3.24)	8 (17)	11 (25)	1	11 (25)
	8a	46 (18)	132 (52)	21-6-9	0.127 (0.050)	Buttweld	19 (42)	◊	Inconel	0.0180 (0.0071)	Buttweld Transition SS	1.47 (3.24)	8 (17)	11 (25)	1	11 (25)
	"	"	"	" "	" "	" "	"	◊	Aluminum	0.0803 (0.0316)	" "	1.47 (3.24)	8.62 (19)	10.38 (23)	1	10.38 (23)
	"	"	"	" "	" "	" "	"	◊	304L	0.0589 (0.0232)	" "	1.47 (3.24)	13.15 (29)	5.85 (13)	1	5.85 (13)
	"	"	"	" "	" "	" "	"	◊	21-6-9	0.0183 (0.0072)	" "	1.47 (3.24)	7.26 (16)	11.74 (26)	1	11.74 (26)
Orbiter Main Engine LH_2 Feedline	2	31 (12)	163 (64)	21-6-9	0.127 (0.050)	Buttweld	16 (35)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	.98 (2.16)	4 (9)	12 (26)	1	12 (26)
	"	"	"	" "	" "	" "	"	◊	Aluminum	0.0076 (0.0030)	" "	.98 (2.16)	3.63 (8)	12.37 (27)	1	12.37 (27)
	"	"	"	" "	" "	" "	"	◊	21-6-9	0.0076 (0.0030)	" "	.98 (2.16)	4.08 (9)	11.92 (26)	1	11.92 (26)
	5	31 (12)	122 (48)	21-6-9	0.127 (0.050)	Buttweld	12 (26)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	.98 (2.16)	4 (8)	8 (18)	1	8 (18)

TABLE E-1. - WEIGHT SAVINGS OBTAINABLE BY USE OF COMPOSITE LINES IN THE SPACE SHUTTLE VEHICLE (Continued)

DESCRIPTION	SECTION CODE	DIAMETER cm (in.)	LENGTH cm (in.)	PHASE B CONFIGURATION				COMPOSITE CONFIGURATION						WEIGHT SAVINGS/ SECTION kg (lbs)	NO. OF SECTIONS	TOTAL WEIGHT SAVINGS kg (lbs)
				MATERIAL	WALL THICKNESS cm (in.)	END FITTING	SECTION TOTAL WT. kg (lbs)	END FITTING CODE	LINER MATERIAL	LINER THICKNESS cm (in.)	END FITTING	END FITTING TOTAL WT. kg (lbs)	SECTION TOTAL WT. kg (lbs)			
Orbiter OMS LOX Feedline	1a	5.5 (2.17)	114 (45)	21-6-9	.041 (0.016)	Conoseal SS Buttweld	1.5 (3.39)	△	Inconel	0.0089 (0.0035)	Conoseal SS Transition SS	0.91 (2.00) 0.027 (0.06)	1.3 (3.03)	0.2 (0.36)	2	0.4 (0.72)
	2	6.7 (2.65)	381 (150)	21-6-9	0.041 (0.016	Buttweld	2.6 (5.71)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.068 (0.15)	1.8 (3.94)	0.80 (1.77)	1	0.80 (1.77)
	3a	6.7 (2.65)	179 (70)	21-6-9	0.041 (0.016)	Conoseal SS Buttweld	2.3 (5.12)	△	Inconel	0.0076 (0.0030)	Conoseal SS Buttweld Transition SS	1.11 (2.45) 0.036 (0.08)	2.0 (4.37)	0.3 (0.75)	2	0.6 (1.5)
	4	6.7 (2.65	135 (53)	21-6-9	0.041 (0.016)	Buttweld	0.9 (2.02)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.068 (0.15)	0.7 (1.64)	0.2 (0.38)	2	0.4 (0.76)
Orbiter OMS LH_2 Feedline	1a	9.9 (3.9)	394 (155)	21-6-9	0.050 (0.020)	Buttweld	4.9 (10.86)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.13 (0.28)	2.2 (4.92)	2.7 (5.94)	1	2.7 (5.94)
	1b	9.9 (3.9)	137 (54)	21-6-9	0.050 (0.020)	Conoseal SS Buttweld	3.2 (7.08)	△	Inconel	0.0076 (0.0030)	Conoseal SS Transition SS	1.5 (3.3) 0.06 (0.14)	2.5 (5.44)	0.7 (1.64)	1	0.7 (1.64)
	2	9.9 (3.9)	1460 (575)	21-6-9	0.050 (0.020)	Buttweld	18 (40.3)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.13 (0.28)	9.8 (21.63)	8.2 (18.67)	1	8.2 (18.67)
	3a	9.9 (3.9)	345 (136)	21-6-9	0.050 (0.020)	Buttweld	4.3 (9.53)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.13 (0.28)	2.4 (5.33)	1.9 (4.20)	1	1.9 (4.20)
	4	7.9 (3.1)	681 (268)	21-6-9	0.050 (0.020)	Buttweld	6.8 (14.93)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.10 (0.22)	3.7 (8.14)	3.1 (6.79)	1	3.1 (6.79)
	5	7.9 (3.1)	335 (132)	21-6-9	0.050 (0.020)	Buttweld	3.3 (7.35)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.10 (0.22)	1.9 (4.12)	1.4 (3.23)	2	2.8 (6.46)

TABLE E-1. - WEIGHT SAVINGS OBTAINABLE BY USE OF COMPOSITE LINES IN THE SPACE SHUTTLE VEHICLE (Concluded)

DESCRIPTION	SECTION CODE	DIAMETER cm (in.)	LENGTH cm (in.)	PHASE B CONFIGURATION				COMPOSITE CONFIGURATION						WEIGHT SAVINGS/ SECTION kg (lbs)	NO. OF SECTIONS	TOTAL WEIGHT SAVINGS kg (lbs)
				MATERIAL	WALL THICKNESS cm (in.)	END FITTING	SECTION TOTAL WT. kg (lbs)	END FITTING CODE	LINER MATERIAL	LINER THICKNESS cm (in.)	END FITTING	END FITTING TOTAL WT. kg (lbs)	SECTION TOTAL WT. kg (lbs)			
Orbiter OMS LH_2 Feedline	6a	7.87 (3.1)	226 (89)	21-6-9	0.05 (0.020)	Buttweld	2.3 (4.96)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition SS	0.10 (0.22)	1.30 (2.85)	1.0 (2.11)	2	2.0 (4.2)
	7a	7.87 (3.1)	51 (20)	21-6-9	0.05 (0.020)	Conoseal SS Buttweld	1.7 (3.81)	△	Inconel	0.0076 (0.0030)	Conoseal SS Buttweld Transition SS	1.23 (2.7) 0.05 (0.11)	1.50 (3.40)	0.2 (0.41)	2	0.4 (0.80)
ACPS LOX Feedline	1	2.95 (1.16)	508 (200)	Aluminum	0.07 (0.028)	Buttweld	1.0 (0.94)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition	0.06 (0.12)	1.07 (2.36)	-0.13 (-0.28)	1	
	2a	2.95 (1.16)	79 (31)	Aluminum	0.07 (0.028)	Buttweld	0.2 (0.14)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition	0.06 (0.12)	0.20 (0.44)	-0.06 (-0.12)	1	
ACPS LH_2 Feedline	1a	3.63 (1.43)	254 (100)	Aluminum	0.07 (0.028)	Buttweld	0.6 (0.58)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition	0.06 (0.14)	0.69 (1.52)	-0.11 (-0.24)	1	
	3a	3.63 (1.43)	457 (180)	Aluminum	0.07 (0.028)	Buttweld	1.0 (1.05)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition	0.06 (0.14)	1.19 (2.62)	-0.14 (-0.31)	1	
	3b	3.63 (1.43)	56 (22)	Aluminum	0.07 (0.028)	Buttweld	0.1 (0.13)	◊	Inconel	0.0076 (0.0030)	Buttweld Transition	0.06 (0.14)	0.20 (0.44)	-0.07 (-0.16)	1	

APPENDIX F

WEIGHT AND COST TRADE STUDY

ALL-METAL vs. COMPOSITE PROPULSION LINES

FOR THE SPACE SHUTTLE

EXTERNAL TANK

APPENDIX F

TABLES

FIGURES

INTRODUCTION

The purpose of this study was to compare the cost and weight of composite tubing with the more conventional all-metal tubing using Space Shuttle propulsion system line configurations. The economic feasibility of composite tubing is dependent on the cost per pound of weight reduced applicable to the Space Shuttle external tank. This allowable cost is currently defined as approximately $66/kg ($30/pound) for the 449 vehicles planned.

The study shows that composite tubing is cost effective for four of the five systems considered during the years of high production and also for the total program. Composite tubing is not shown cost effective during the first few years of low production due to the initial investment required for equipment and facilities. It is feasible, however, to produce composite tubing in the quantities required for two ship sets per year at the existing Martin Marietta Corporation composites facility which has produced flight qualified hardware using composites. If this was done, major capital investment could be delayed until the fourth or fifth year of the program, and the costs during the low production years would be approximately equal to the costs during high production.

ASSUMPTIONS FOR COST AND WEIGHT CALCULATIONS

A series of assumptions or ground rules were developed to form the baseline for the evaluation. These include:

- The costs that are common to both all-metal and composite lines are excluded from the trade study and are defined as follows:

  a) Development and qualification testing. (NOTE: Leak checks and other detail level inspections were included);

  b) Tube design;

  c) Fittings (bellows, elbows, swivels, supports, etc.);

  d) Pack and ship;

  e) Cleaning;

  f) Final line assembly to the external tank.

- The all-metal aluminum lines must use an aluminum to stainless steel flange joint at each connection with a stainless steel fitting, such as at all bellows, gimbal joints, etc. The weight and costs of the flanges plus the cost for welding the aluminum flange halves to the aluminum lines are included in the all-metal line analysis. The composite lines use stainless steel end fittings and can be welded directly to the stainless steel fittings without a requirement for flanged connections.

- Only the straight line lengths are currently candidates for composite tubing and were considered for cost and weight comparison. Curved tubing technology may be explored in a follow-on contract.

- It is assumed that high temperature composites capable of withstanding the 678 K (760°F) operating temperature required for the LOX pressurization line will be developed.

- Minimum gage allowable was assumed to equal 0.117 cm (0.046 in.) for both all-metal and composite lines.

- Assumed external tank fabrication schedule is shown in Table F-1.

TABLE F-1. - EXTERNAL TANK FABRICATION SCHEDULE

SHIP SET NO.	QUANTITY	DELIVERY DATE
	2	08/01/74
	1	01/01/75
	1	12/01/75
1	1	05/01/76
2	1	10/01/76
3	1	03/01/77
4	1	08/01/77
5	1	01/01/78
6	1	06/01/78
7 - 21	15	06/01/79
22 - 47	24	05/01/80
48 - 79	32	05/01/81
80 - 119	40	05/01/82
120 - 179	60	05/01/83
180 - 239	60	05/01/84
240 - 299	60	05/01/85
300 - 359	60	05/01/86
360 - 419	60	05/01/87
420 - 445	30	05/01/88
TOTAL:	449 Ship Sets	

o All costs were based on projected 1974 salary levels.

COST ELEMENTS AND SOURCES OF DATA

Three separate cost elements were evaluated including start-up, composite lines, and all-metal lines. This section defines the cost elements which were included. Bids were provided by three vendors, using two different concepts for the composite lines, and for the all-metal lines. Throughout this study vendor 1 refers to two vendors.

Start-Up Costs. - These are costs for initial investment required to produce composite lines and/or all-metal lines in the sizes and quantities required for the Space Shuttle. The initial investment required by vendor 1 and vendor 2 are included in their price quotes and are amortized in the cost per ship set as defined in the detailed cost analysis.

Composite Lines. - The two primary cost elements associated with the production of composite lines are: 1) the metal liners; and 2) the application of the glass-fiber overwrap.

The costs for the metal liners consists of:

- Liner material (flat sheet);
- Rolling the liner material into a tube and welding;
- Heat treat;
- End fitting material and machining;
- Welding end fittings onto each end of the tube;
- Low pressure leak test;
- Inspection and quality control;
- Shipping from vendor to Denver.

The costs for the metal liners used in this trade study are based on price quotes from vendors 1 and 2. All vendors have participated in the composite line development contracts and are capable of producing metal liners in the sizes and quantities required for Space Shuttle.

The costs for material and machining of end fittings was not included in the quote from vendor 2. These costs were estimated by a local vendor and added to the quote to obtain a comparison.

The costs for the application of the glass-fiber overwrap consist of:

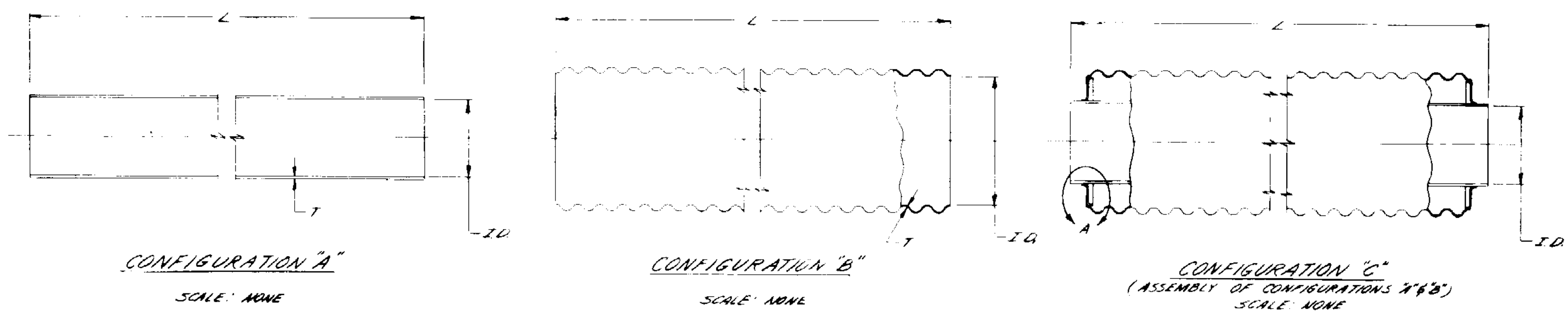
- Receiving inspection;
- Storage and handling;
- Glass-fiber material for overwrap;
- Tube surface preparation;
- Apply the overwrap;
- Curing;
- Pressure proof test;
- Leak test;
- Inspection;
- Appropriate factors were included for supervision, production control and tooling.

These costs for the trade study are based on a Martin Marietta Corporation Manufacturing Department cost estimate prepared during the study.

All-Metal Lines. - The costs for the all-metal lines are based on a price quote from vendor 1, plus the costs of the addition of conoseal flanges as defined in the detail cost analysis.

LINE CONFIGURATIONS

The Space Shuttle line configurations depicted in Figures 2 through 4 of the main report were used to determine line lengths and to develop the all-metal and composite line configurations depicted in Figures F-1 and F-2, for cost and weight analysis.



ALL METAL LINE REQUIREMENTS FOR ONE SHIP SET

BUILD PACKAGE	DESCRIPTION FUNCTION/COMMODITY	CONFIGURATION	QTY	I.D (IN)	L (IN)	T (WALL THICKNESS IN INCHES)	TUBE MATERIAL	PRESSURE (PSIG) OPERATING	PROOF	BURST
1	LH2 TANK RECIRCULATION/ LIQUID HYDROGEN	A	1	4	44	.065	304 SS	45	68	90
			1		32					
			1		49					
		B	1	7	42	.046	304 SS	VACUUM	VACUUM	VACUUM
			1		30					
			1		47					
		C	1	4	44			45 (INNER LINE)	68 (INNER LINE)	90 (INNER LINE)
			1		32					
			1		49					
2	LOX TANK PRESSURIZATION/ GASEOUS OXYGEN	A	1	6	360	.046	304 SS	30	45	60
			1		400					
			3		440					
			1		96					
3	LOX FEED LINE/ LIQUID OXYGEN	A	3	17	425	.140	2219 ALUMINUM	90 250 (SURGE)	375	500
			1		154					
4	LOX RECIRCULATION/ LIQUID OXYGEN	A	1	4	196	.125	2219 ALUMINUM	90 250 (SURGE)	375	500
			3		425					
5	LH2 TANK PRESSURIZATION/ GASEOUS HYDROGEN	A	2	10	115	.063	2219 ALUMINUM	45	68	90
			3		423					
			1		46					
			1		33					

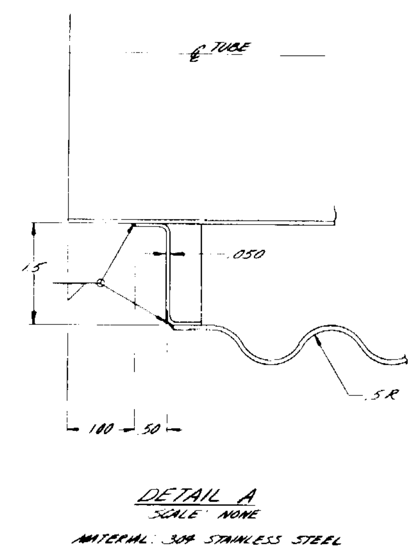
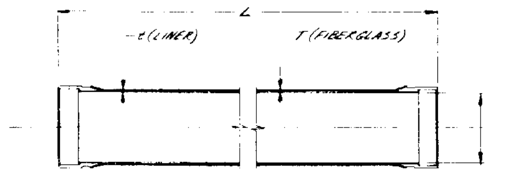
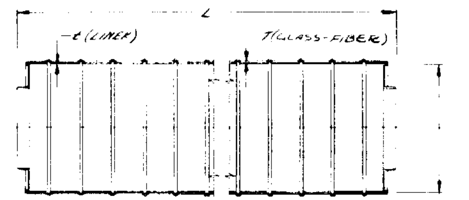


Figure F-1. - All-Metal Line Configurations



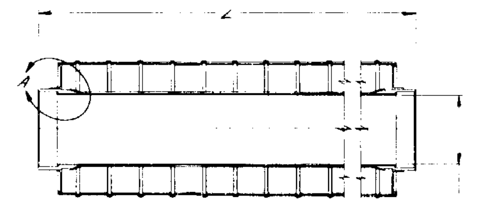
CONFIGURATION "A"

SCALE: NONE



CONFIGURATION "B"

SCALE: NONE



CONFIGURATION "C"

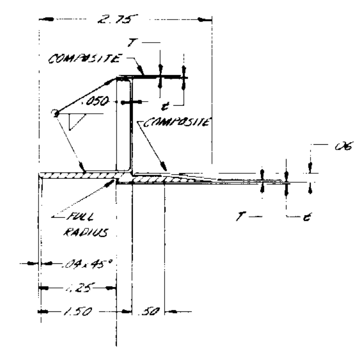
(ASSEMBLY OF CONFIGURATIONS "A" & "B")

SCALE: NONE

COMPOSITE LINE REQUIREMENTS FOR ONE SHIP SET

BUILD PACKAGE	DESCRIPTION FUNCTION / COMMODITY	CONFIG-URATION	QTY	I.D. (IN.)	L (IN.)	TUBE LINER THICKNESS t (IN.)	TOTAL TUBE THICKNESS .024 T	.032 T	.046 T	TUBE MATERIAL	PRESSURE (PSIG) OPERATING	PROOF	BURST
1	LH2 TANK RECIRCULATION/ LIQUID HYDROGEN	A	1	4	44	.006	.020	.028	.044	* INCONEL 718 LINER WITH COMPOSITE	45	68	90
			1		32								
			1		49								
		B	1	7	42	.006				* 304L S.S. LINER WITH COMPOSITE	VACUUM	VACUUM	VACUUM
			1		30								
			1		47								
		C	1	4	44						45 (INNER LINE)	68 (INNER LINE)	90 (INNER LINE)
			1		32								
			1		49								
2	LOX TANK PRESSURIZATION/ GASEOUS OXYGEN	A	3	6	120	.006	.020	.028	.044	* INCONEL 718 LINER WITH COMPOSITE	30	45	60
			3		133								
			11		120								
			1		96								
3	LOX FEED LINE/ LIQUID OXYGEN	A	6	17	211	.013	.024		.032	* INCONEL 718 LINER WITH COMPOSITE	90 250 (SURGE)	375	500
			1		154								
4	LOX RECIRCULATION/ LIQUID OXYGEN	A	2	4	98	.006	.020	.024	.040	* INCONEL 718 LINER WITH COMPOSITE	90 250 (SURGE)	375	500
			11		116								
5	LH2 TANK PRESSURIZATION/ GASEOUS HYDROGEN	A	2	10	115	.006	.020	.028	.044	* INCONEL 718 LINER WITH COMPOSITE	45	68	90
			11		115								
			1		46								
			1		33								

* COMPOSITE MATERIAL IS E-GLASS, 20 END ROVING, WITH 58-68R RESIN SYSTEM.



DETAIL A

SCALE: FULL

MATERIAL: 304 STAINLESS STEEL EXCEPT FOR COMPOSITE

Figure F-2. - Composite Line Configurations

PROPULSION LINE WEIGHTS

Weights were calculated for the all-metal and composite lines excluding the common elements such as elbows, bellows, valves, etc. These weights were based upon a minimum wall thickness of 0.117 cm (0.046 in.) for both the all-metal and composite configurations. Details of these calculations are shown in the following paragraphs.

All-Metal Line Weight (0.117 cm Minimum Gage). - The weights of the all-metal lines include end flanges on the aluminum lines which are required to mate these lines to stainless steel components.

The weight calculation data include:

WEIGHT CALCULATION

BUILD PACKAGE	AVERAGE LINE LENGTH (cm)	LINE DIA. (cm)	MATERIAL AND GAGE (cm)	NUMBER OF LINES	NUMBER OF CONOSEALS
1	107	10 & 18	SS/10 cm, 0.165 18 cm 0.117	3	-
2	919	15	SS, 0.117	6	-
3	902	43	AL, 0.356	4	4
4	935	10	AL, 0.318	4	6
5	572	25.5	AL, 0.160	7	10

Build package No. 1

wt = $\pi(10)(0.165)(107)(0.008)(3)$ = 13.3 kg

$\pi(18)(0.117)(107)(0.008)(3)$ = 17.0

End Fittings: 6 @ 0.27 kg each = 1.6

TOTAL: 31.9 kg (70 lb)

Build package No. 2

wt = $\pi(15)(0.117)(919)(0.008)(6)$ = 243 kg (535 lb)

*Build package No. 3

$$wt = \pi(43)(0.356)(902)(0.003)(4) = 521 \text{ kg}$$

4 conoseals @ 10 kg ea.	=	40
TOTAL:		561 kg (1,234 lb)

Build package No. 4

$$wt = \pi(10)(0.318)(935)(0.003)(4) = 112.1 \text{ kg}$$

6 conoseals @ 2.3 kg ea.	=	13.8
TOTAL:		125.9 kg (277 lb)

* Conoseal flange weights were obtained from weights engineering. Weights include a stainless steel flange half, an aluminum flange half, seals, clamps, and attaching hardware. (Type: Medium weight double seal).

DIAMETER	WEIGHT
43 cm (17 in.)	10 kg (22 lb)
25.5 cm (10 in.)	6.1 kg (13.5 lb)
10 cm (4 in.)	2.3 kg (5 lb)

Build package No. 5

$$wt = \pi(25.5)(0.160)(572)(0.003)(7) = 154 \text{ kg}$$

10 conoseals @ 6 kg ea.	=	60
TOTAL:		214 kg (470 lb)

Composite Line Weights (0.117 cm Minimum Gage). - The composite line weights consist of a summation of the weights of the metal liners, end fittings, and the overwrap. End fitting weights are provided in Figures F-3 and F-4. Weights are based on an overwrap density of 0.0024 kg/cm^3 (0.085 lb/in.^{3}) and an Inconel density of 0.008 kg/cm^3 (0.29 lb/in.^{3}). Conoseals are not required for the composite concept.

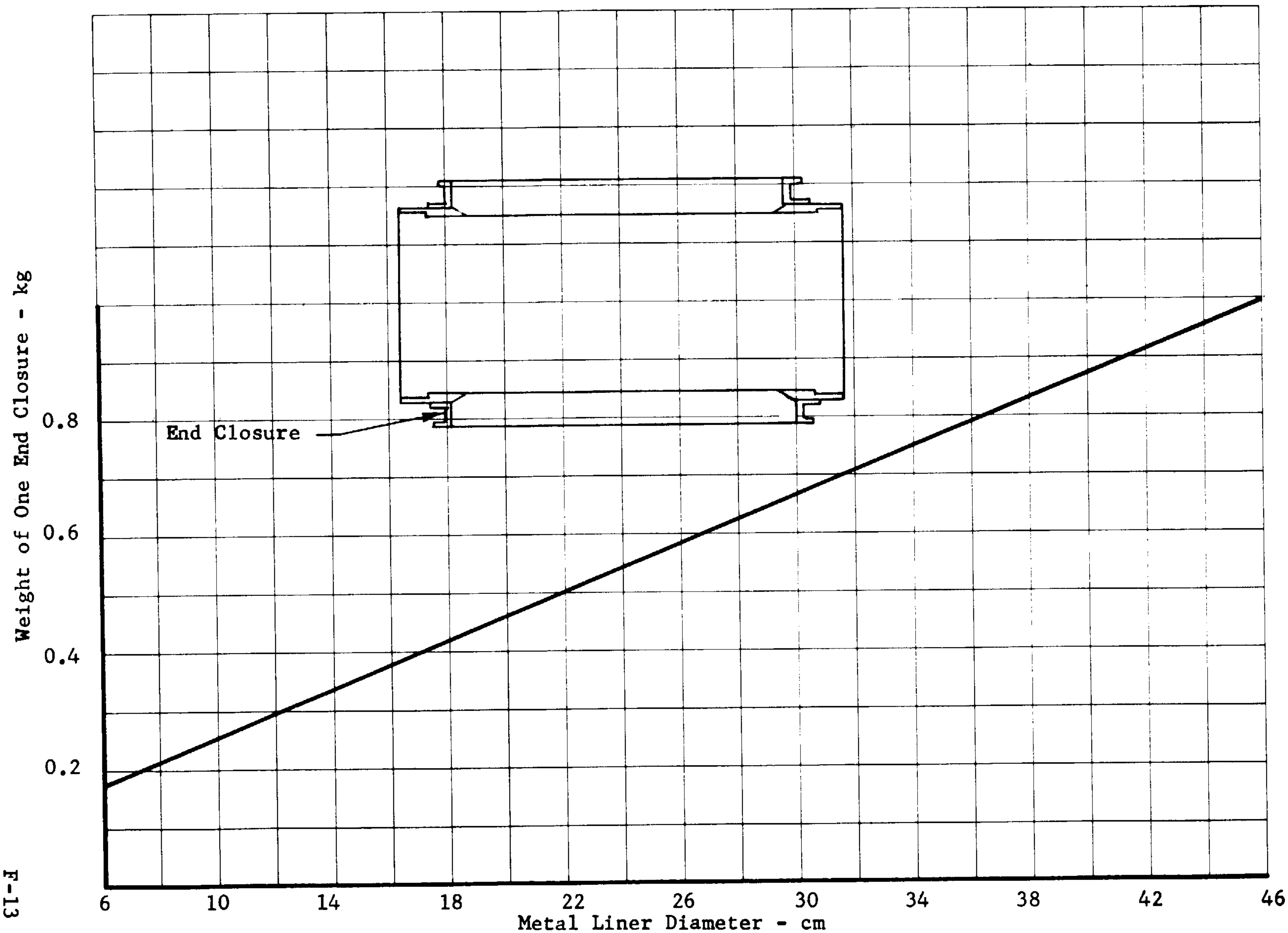


Figure F-3. - Stainless Steel Vacuum Jacket End Closure Weight

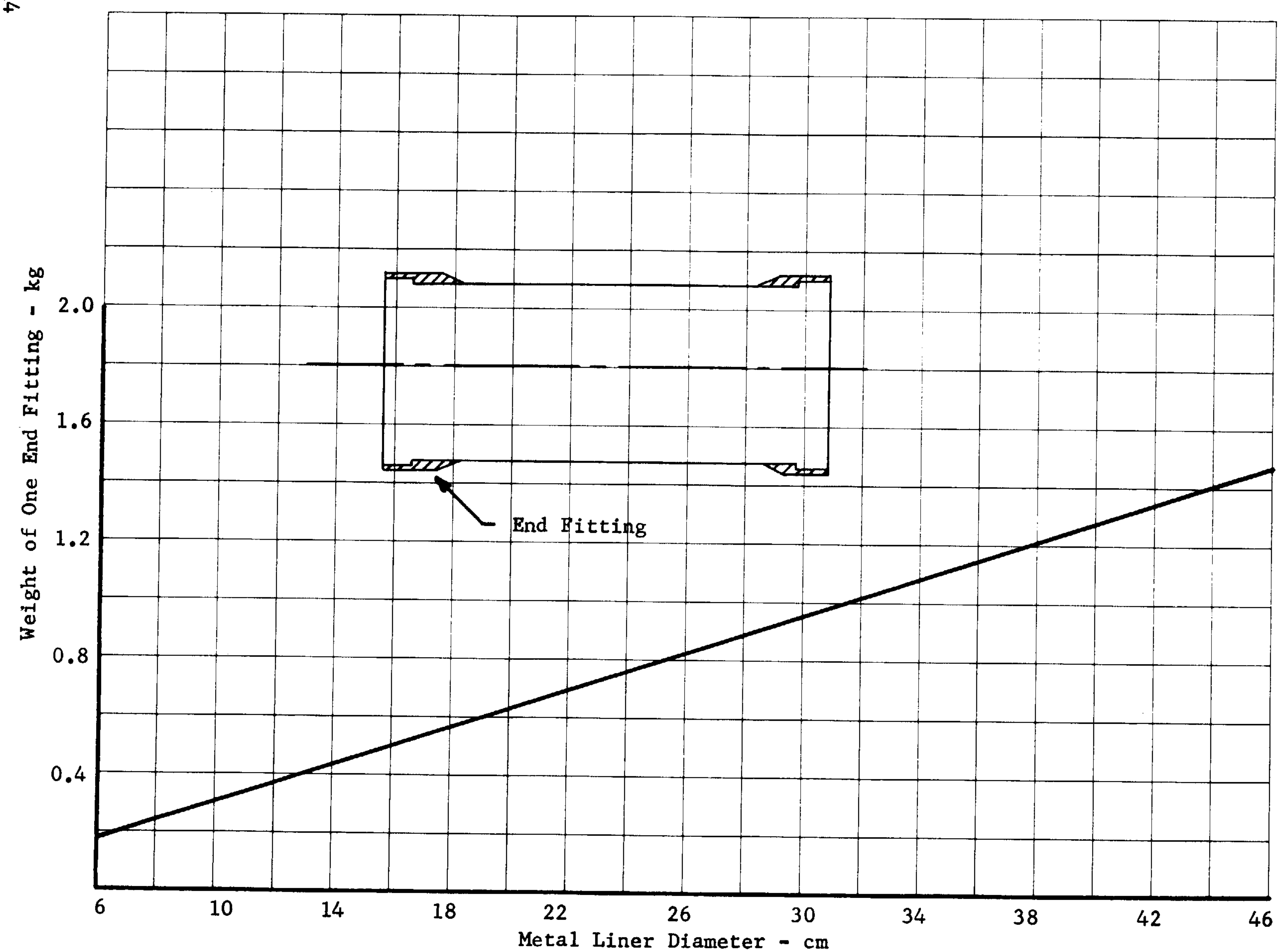


Figure F-4. - Stainless Steel End Fitting Weight (Composite Liners)

WEIGHT CALCULATION DATA

BUILD PACKAGE	AVERAGE LINE LENGTH (cm)	LINE DIAMETER (cm)	METAL GAGE (cm)	COMPOSITE GAGE (cm)	NUMBER OF LINES
1	107	10 & 18	0.015	0.10	3
2	307	15	0.015	0.10	18
3	516	43	0.033	0.08	7
4	290	10	0.015	0.10	13
5	267	25.5	0.015	0.10	15

<u>Build package No. 1</u>

Inner Liner:	$\pi(10)(0.015)(107)(0.008)(3)$	=	1.2 kg
End Fittings:	6 @ 0.32 kg ea.	=	1.9
Overwrap:	$\pi(10)(0.051)(107)(0.0024)(3)$	=	1.2
Vacuum Jacket:	$\pi(18)(0.015)(107)(0.008)(3)$	=	2.2
End Fittings:	6 @ 0.27 kg ea.	=	1.6
Overwrap:	$\pi(18)(0.10)(107)(0.0024)(3)$	=	4.4
	TOTAL:		12.5 kg (27 lb)

<u>Build package No. 2</u>

Liner:	$\pi(15)(0.015)(307)(0.008)(18)$	=	31 kg
End Fittings:	36 @ 0.48 kg ea.	=	17
Overwrap:	$\pi(15)(0.10)(307)(0.0024)(18)$	=	63
	TOTAL:		111 kg (244 lb)

Build package No. 3

Liner:	$\pi(43)(0.033)(516)(0.008)(7)$	=	129.0 kg
End Fittings:	14 @ 1.4 kg ea.	=	19.6
Overwrap:	$\pi(43)(0.08)(516)(0.0024)(7)$	=	93.7
	TOTAL:		242.3 kg (533 lb)

Build package No. 4

Liner:	$\pi(10)(0.015)(290)(0.008)(13)$	=	14.2 kg
End Fittings:	26 @ 0.32 kg ea.	=	8.3
Overwrap:	$\pi(10)(0.10)(290)(0.0024)(13)$	=	28.4
	TOTAL:		50.9 kg (112 lb)

Build package No. 5

Liner:	$\pi(25.5)(0.015)(267)(0.008)(15)$	=	38.5 kg
End Fittings:	30 @ 0.8 kg ea.	=	24.0
Overwrap:	$\pi(25.5)(0.10)(267)(0.0024)(15)$	=	77.0
	TOTAL:		139.5 kg (307 lb)

PROPULSION LINE COSTS

Cost comparisons were prepared for the all-metal and composite lines, again excluding the common elements. The liner costs were obtained from three separate vendors using two different fabrication techniques. They are identified as Vendor 1 and Vendor 2, representative of each technique.

All-Metal Line Costs. - The all-metal line costs include the costs for engineering, setup, material, fabrication, inspection, leak test and shipment from the Vendor to Denver. The aluminum all-metal lines have the added cost of conoseal flanges where required to mate with stainless steel fittings.

The non-recurring engineering and setup costs per build package were provided in the price quotation from Vendor 1. These costs were amortized in dollars per build package (D/BP) based on yearly production quantities as follows:

For ship sets No. 1 thru 6 and No. 120 thru 179:

$$D/BP = \frac{\text{Cost per Build Package}}{\text{14 Years}} \times \frac{1}{\text{No. Ship Sets Produced Per Year}}$$

For 449 ship sets:

$$D/BP = \frac{\text{Cost per Build Package}}{449}.$$

The costs for conoseal flanges, clamps and attaching hardware are based on a telecon quote from the conoseal manufacturer, based on a quantity of 360 flanges and are as follows:

DIAMETER	STAINLESS STEEL HALF	ALUMINUM HALF
10 cm (4 in.)	$ 83 ea.	$ 50 ea.
25.5 cm (10 in.)	310 ea.	200 ea.
43 cm (17 in.)	540 ea.	350 ea.

The costs for welding the aluminum conoseal flanges to the aluminum lines are based on 2.5 hours labor for 30 cm (12 in.) of weld.

The costs for dye penetrant test of welds and leak checks, required for the installation of the conoseal flanges were based on 1 hour labor per flange.

Average cost per ship set for ship sets No. 1 thru 6:

BUILD PACKAGE	UNIT COST	ENGR & SETUP	CONOSEAL FLANGES	WELDING CONO- SEAL FLANGES	DYE PEN. & LEAK TESTS	TOTAL
1	$2,122	$171	-	-	-	$ 2,293
2	2,950	43	-	-	-	2,993
3	2,419	60	$3,560	$612	$ 55	6,706
4	1,418	60	798	217	83	2,576
5	3,552	517	5,100	905	138	10,212

Average cost per ship set for ship sets No. 120 thru 179:

BUILD PACKAGE	UNIT COST	ENGR & SETUP	CONOSEAL FLANGES	WELDING CONO- SEAL FLANGES	DYE PEN. & LEAK TESTS	TOTAL
1	$1,069	$ 6	-	-	-	$1,075
2	1,650	1	-	-	-	1,651
3	1,353	2	$3,560	$612	$ 55	5,582
4	832	2	798	217	83	1,932
5	1,986	17	5,100	905	138	8,146

Average cost per ship set for 449 ship sets:

BUILD PACKAGE	UNIT COST	ENGR & SETUP	CONOSEAL FLANGES	WELDING CONO- SEAL FLANGES	DYE PEN. & LEAK TESTS	TOTAL
1	$1,143	$ 11	-	-	-	$1,154
2	1,664	3	-	-	-	1,667
3	1,997	4	$3,560	$612	$ 55	6,228
4	984	4	798	217	83	2,086
5	2,160	32	5,100	905	138	8,335

Summary of Composite Line Costs. - The total composite line costs were prepared for each metal liner concept and are included. The total composite line costs based on liners procured from Vendor 1 are shown in Table F-2. The total composite line costs based on liners procured from Vendor 2 are shown in Table F-3.

TABLE F-2. - COMPOSITE LINE COSTS USING VENDOR 1

BUILD PACKAGE	AVERAGE UNIT COST FOR FIRST 6 SHIP SETS	AVERAGE UNIT COST FOR SHIP SETS NO. 120 THRU 179	AVERAGE UNIT COST FOR 449 SHIP SETS
1	$ 10,122	$ 2,595	$ 3,184
2	30,506	8,525	10,707
3	39,543	12,512	14,950
4	11,204	3,501	4,356
5	26,912	8,584	10,159
TOTAL:	$118,287	$35,717	$43,356

TABLE F-3. - COMPOSITE LINE COSTS USING VENDOR 2

BUILD PACKAGE	AVERAGE UNIT COST FOR FIRST 6 SHIP SETS	AVERAGE UNIT COST FOR SHIP SETS NO. 120 THRU 179	AVERAGE UNIT COST FOR 449 SHIP SETS
1	$ 11,348	$ 3,236	$ 4,017
2	40,918	12,985	14,053
3	52,408	17,014	17,557
4	18,806	6,845	6,894
5	37,622	13,108	13,338
TOTAL:	$161,102	$53,188	$55,859

Metal liner costs - Vendor 1: The metal liner costs include all costs for engineering, tooling, material, fabrication, inspection, leak test and shipment from the vendor to Denver.

Engineering and tooling non-recurring (NR) costs are amortized as follows:

BUILD PACKAGE	TOTAL NR COSTS	COST/YEAR OVER 14 YEARS	AVERAGE COST/ SHIP SET FOR FIRST 6	AVERAGE COST/ SHIP SET FOR 60	AVERAGE COST/ SHIP SET FOR 449
1	$ 4,800	$ 343	$ 176	$ 3	$11
2	7,800	557	278	5	17
3	14,600	1,043	521	9	32
4	4,200	300	150	3	9
5	14,600	1,042	521	8	32

The metal liner cost summary is shown in Table F-4.

TABLE F-4. - METAL LINER COSTS - VENDOR 1

(For Ship Sets No. 1 thru 6)

BUILD PACKAGE	LINER FABRICATION	NEW EQUIPMENT	END FITTINGS	TOTAL
1	$ 2,208	$ 176	*	$ 2,384
2	6,762	278		7,040
3	13,075	521		13,596
4	3,519	150		3,669
5	8,935	521		9,456
TOTAL:	$34,499	$1,646	---	$36,145

* End fitting costs are included in liner fabrication costs.

TABLE F-4 (Concluded)

(For Ship Sets No. 120 thru 179)

BUILD PACKAGE	LINER FABRICATION	NEW EQUIPMENT	END FITTINGS	TOTAL
1	$ 1,139	$ 3	*	$ 1,142
2	3,489	5		3,494
3	6,746	9		6,755
4	1,816	3		1,819
5	4,610	8		4,618
TOTAL:	$17,800	$28	---	$17,828

(Average Cost for 449 Ship Sets)

BUILD PACKAGE	LINER FABRICATION	NEW EQUIPMENT	END FITTINGS	TOTAL
1	$ 835	$ 11	*	$ 846
2	3,978	17		3,995
3	7,543	32		7,575
4	2,225	9		2,234
5	5,219	32		5,251
TOTAL:	$19,800	$101	---	$19,901

* End fitting costs are included in liner fabrication costs.

Metal liner costs - Vendor 2: The metal liner costs include all costs for investment in new equipment, material, fabrication, inspection, leak test, and shipment from the vendor to Denver. The metal liner end fittings are provided by Martin Marietta Corporation and costs are included in the table. An amortization of an investment in new equipment is included at the following levels:

Amortize $80,000 over 14 years = $ 5,714/year

Amortize $80,000 over 10 years = $ 8,000/year, therefore,

for years 1974 thru 1978, $ 5,714/year was amortized and

for years 1979 thru 1988, $13,715/year was amortized.

The amortization schedule per ship set is as follows:

First 6 ship sets: $ 2,857/ship set

Year 1983 60 ship sets/year: $ 288/ship set

Average over 449 ship sets: $ 356/ship set

The costs for end fittings are based on actual procurement experience on the NAS3-16762 contract for small quantities and a telecon quote from a local machine shop for quantities required for two ship sets per year and for 60 ship sets per year.

BUILD PACKAGE	QUANTITY REQUIRED PER SHIP SET	UNIT COST FOR FIRST 6 SHIP SETS	UNIT COST BASED ON 60 SHIP SETS	FITTING COST PER SHIP SET BASED ON 6	FITTING COST PER SHIP SET BASED ON 60
1	6 - 10 cm Dia.	$ 55	$46	$ 330	$ 276
	6 - 18 cm Dia.	75	63	450	378
2	38 - 15 cm Dia.	60	50	2,160	1,800
3	14 - 43 cm Dia.	100	84	1,400	1,176
4	26 - 10 cm Dia.	55	46	1,430	1,196
5	30 - 25.5 cm Dia.	80	67	2,400	2,010

The metal liner cost summary is shown in Table F-5.

TABLE F-5. - METAL LINER COSTS - VENDOR 2

(For Ship Sets No. 1 thru 6)

BUILD PACKAGE	LINER FABRICATION	NEW EQUIPMENT	END FITTINGS	TOTAL
1	$ 2,717	$ 113	$ 780	$ 3,610
2	14,674	618	2,160	17,452
3	24,049	1,012	1,400	26,461
4	9,443	398	1,430	11,271
5	17,051	716	2,400	20,167
TOTAL:	$67,934	$2,857	$8,170	$78,961

(For Ship Sets No. 120 thru 179 (60 Ship Sets)

BUILD PACKAGE	LINER FABRICATION	NEW EQUIPMENT	END FITTINGS	TOTAL
1	$ 1,120	$ 9	$ 654	$ 1,783
2	6,105	49	1,800	7,954
3	10,000	81	1,176	11,257
4	3,935	32	1,196	5,163
5	7,075	57	2,010	9,142
TOTAL:	$28,235	$228	$6,836	$35,299

TABLE F-5 (Concluded)

(Average Cost for 449 Ship Sets)

BUILD PACKAGE	LINER FABRICATION	NEW EQUIPMENT	*END FITTINGS	TOTAL
1	$ 1,011	$ 14	$ 654	$ 1,679
2	5,464	77	1,800	7,341
3	8,962	44	1,176	10,182
4	3,527	49	1,196	4,772
5	6,331	89	2,010	8,430
TOTAL:	$25,295	$273	$6,836	$32,404

* End fitting costs were assumed to be identical for 449 ship sets to the costs for 60 ship sets.

Costs for adding glass-fiber overwrap to metal liners: The overwrap costs include receiving inspection, storage, handling, recurring and non-recurring tooling, overwrapping, curing, leak test, and inspection. Appropriate factors are included for supervision, production control, tooling and learning. Costs are based on a 1974 rate projection including overhead.

Glass-fiber overwrap material costs are included and are based on a telecon quote from a vendor. A 15% waste factor was added to the required weight and is included in the costs.

The fabrication costs summary, including material, is included:

BUILD PACKAGE	AVERAGE UNIT COST FOR FIRST 6 SHIP SETS	AVERAGE UNIT COST FOR SHIP SETS NO. 120 THRU 179	AVERAGE UNIT COST FOR 449 SHIP SETS
1	$ 7,738	$1,453	$2,338
2	23,466	5,031	6,712
3	25,947	5,757	7,375
4	7,535	1,682	2,122
5	17,456	3,966	4,908

Costs for the first 6 ship sets could be reduced to approximately the same as the average unit costs for 449 ship sets by the use of the existing composites facility at Martin Marietta Corporation.

WEIGHT/COST SUMMARY

The total line weights (excluding fitting weight common to both all-metal and composite lines), costs, and the cost/pound saved by the use of composite lines are summarized in Table F-6. The "Break Even" column in the table is determined by dividing the Δcost by Δweight and it provides the cost to reduce weight by use of composite lines, which can be compared to the cost of weight to orbit, currently estimated at $66/kg ($30/lb).

TABLE F-6. - WEIGHT/COST SUMMARY

[All-Metal vs. Composite Lines for Space Shuttle External Tanks]

[Average Unit Costs for 449 Ship Sets, Based on Vendor 1 Quote]

Build Package	System	Weight (kg)			Cost ($)			Break Even $/kg ($/1b)
		M	C	Δ	M	C	Δ	
1	LH_2 Tank Recirculation (Vacuum Jacketed) 10 cm I.D. x 317 cm long	32	12.5	19.5	$1154	$3184	$2030	$104/kg ($47/1b)
2	LOX Tank Pressurization 15 cm I.D. x 5525 cm long	243	111	132	1667	10707	9040	$68/kg ($30/1b)
3	LOX Feedline 43 cm I.D. x 3607 cm long	561	242	319	6228	14950	8722	$26/kg ($12/1b)
4	LOX Recirculation 10 cm I.D. x 3739 cm long	126	51	75	2086	4356	2270	$30/kg ($14/1b)
5	LH_2 Tank Pressurization 25.5 cm I.D. x 4011 cm long	214	140	74	8335	10159	1824	$25/kg ($11/1b)
	TOTAL:	1176	556.5	619.5	19470	43356	23886	

M - All-metal Line
C - Composite Line
Δ - All-metal Line Minus Composite Line (kg or $)

TABLE F-6. - WEIGHT/COST SUMMARY (Continued)

[All-Metal vs. Composite Lines for Space Shuttle External Tank]

[Average Unit Costs for 449 Ship Sets, Based on Vendor 2 Quote]

Build Package	System	Weight (kg)			Cost ($)			Break Even $/kg ($/1b)
		M	C	Δ	M	C	Δ	
1	LH_2 Tank Recirculation (Vacuum Jacketed) 10 cm I.D. x 317 cm long	32	12.5	19.5	$954	$4017	$3063	$157/kg ($71/1b)
2	LOX Tank Pressurization 15 cm I.D. x 5525 cm long	243	111	132	1667	14053	12386	$94/kg ($43/1b)
3	LOX Feedline 43 cm I.D. x 3607 cm long	561	242	319	6228	17557	11329	$33/kg ($15/1b)
4	LOX Recirculation 10 cm I.D. x 3739 cm long	126	51	75	2086	6894	4808	$64/kg ($29/1b)
5	LH_2 Tank Pressurization 25.5 cm I.D. x 4011 cm long	214	140	74	8335	13338	5003	$68/kg ($31/1b)
	TOTAL:	1176	556.5	619.5	19270	55859	36589	

M - All-metal Line
C - Composite Line
Δ - All-metal Line Minus Composite Line (kg or $)

TABLE F-6. - WEIGHT/COST SUMMARY (Continued)

[All-Metal vs. Composite Lines for Space Shuttle External Tank]

[Average unit costs for Ship Sets No. 120 thru 179 (Year 1983) Based on Vendor 1 Quote]

Build Package	System	Weight (kg)			Cost ($)			Break Even $/kg ($/lb)
		M	C	Δ	M	C	Δ	
1	LH_2 Tank Recirculation (Vacuum Jacketed) 10 cm I.D. x 317 cm long	32	12.5	19.5	$1075	$2595	$1520	$78/kg) ($35/lb)
2	LOX Tank Pressurization 15 cm I.D. x 5525 cm long	243	111	132	1651	8525	6874	$52/kg ($24/lb)
3	LOX Feedline 43 cm I.D. x 3607 cm long	561	242	319	5582	12512	6930	$20/kg ($ 9/lb)
4	LOX Recirculation 10 cm I.D. x 3739 cm long	126	51	75	1932	3501	1569	$21/kg ($10/lb)
5	LH_2 Tank Pressurization 25.5 cm I.D. x 4011 cm long	214	140	74	8146	8584	438	$6/kg ($3/lb)
	TOTAL:	1176	556.5	619.5	18386	35717	17331	

M - All-metal Line
C - Composite Line
Δ - All-metal Line Minus Composite Line (kg or $)

TABLE F-6. - WEIGHT/COST SUMMARY (Continued)

[All-Metal vs. Composite Lines for Space Shuttle External Tank]

[Average Unit Cost for Ship Sets No. 120 thru 179 (Year 1983), Based on Vendor 2 Quote]

Build Package	System	Weight (kg)			Cost ($)			Break Even $/kg ($/lb)
		M	C	Δ	M	C	Δ	
1	LH_2 Reciculation (Vacuum Jacketed) 10 cm I.D. x 317 cm long	32	12.5	19.5	$1075	$3236	$2161	$111/kg ($50/lb)
2	LOX Tank Pressurization 15 cm I.D. x 5525 cm long	243	111	132	1651	12985	11334	$86/kg ($39/lb)
3	LOX Feedline 43 cm I.D. x 3607 cm long	561	242	319	5582	17014	11432	$34/kg ($15/lb)
4	LOX Recirculation 10 cm I.D. x 3739 cm long	126	51	75	1932	6845	4913	$66/kg ($30/lb)
5	LH_2 Tank Pressurization 25.5 cm I.D. x 4011 cm long	214	140	74	8146	13108	4962	$67/kg (31/lb)
	TOTAL:	1176	556.5	619.5	18386	53188	34802	

M - All-metal Line
C - Composite Line
Δ - All-metal Line Minus Composite Line (kg or $)

TABLE F-6. - WEIGHT/COST SUMMARY (Continued)

[All-Metal vs. Composite Lines for Space Shuttle External Tank]

[Average Unit Cost for Ship Sets No. 1 thru 6 (Years 1976 thru 1978), Based on Vendor 1 Quote]

Build Package	System	Weight (kg)			Cost ($)			+Break Even $/kg ($/lb)
		M	C	Δ	M	C	Δ	
1	LH_2 Tank Recirculation (Vacuum Jacketed) 10 cm I.D. x 317 cm long	32	12.5	19.5	$2293	$10122	$7829	$401/kg ($182/lb)
2	LOX Tank Pressurization 15 cm I.D. x 5525 cm long	243	111	132	2993	30506	27513	$208/kg ($95/lb)
3	LOX Feedline 43 cm I.D. x 3607 cm long	561	242	319	6706	39543	32837	$97/kg ($44/lb)
4	LOX Recirculation 10 cm I.D. x 3739 cm long	126	51	75	2576	11204	8628	$115/kg ($52/lb)
5	LH_2 Tank Pressurization 25.5 cm I.D. x 4011 cm long	214	140	74	10212	26912	16700	$226/kg ($102/lb)
	TOTAL:	1176	556.5	619.5	24780	118287	93507	

M - All-metal Line
C - Composite Line
Δ - All-metal Line Minus Composite Line (Kg or $)

\+ Costs are based on a production rate of two per year with work being done in the factory. If work was done in the existing composites laboratory at Martin Marietta, these costs would approximately equal the average for 449 ship sets.

TABLE F-6. - WEIGHT/COST SUMMARY (Concluded)

[All-Metal vs. Composite Lines for Space Shuttle External Tank]

[Average Unit Cost for Ship Sets No. 1 thru 6 (Years 1976 thru 1978), Based on Vendor 2 Quote]

Build Package	System	Weight (kg)			Cost ($)			+Break Even $/kg ($/lb)
		M	C	Δ	M	C	Δ	
1	LH_2 Tank Recirculation (Vacuum Jacketed) 10 cm I.D. x 317 cm long	32	12.5	19.5	$2293	$11348	$9055	$464/kg ($211/lb)
2	LOX Tank Pressurization 15 cm I.D. x 5525 cm long	243	111	132	2993	40918	37925	$287/kg ($131/lb)
3	LOX Feedline 43 cm I.D. x 3607 cm long	561	242	319	6706	52408	45702	$135/kg ($ 61/lb)
4	LOX Recirculation 10 cm I.D. x 3739 cm long	126	51	75	2576	18806	16230	$216/kg ($98/lb)
5	LH_2 Tank Pressurization 25.5 cm I.D. x 4011 cm long	214	140	74	10212	37622	27410	$370/kg ($168/lb)
	TOTAL:	1176	556.5	619.5	24780	161102	136322	

M - All-metal Line
C - Composite Line
Δ - All-metal Line Minus Composite Line (kg or $)

+ Costs are based on a production rate of two per year with the work being done in the factory. If work was done in the existing composites laboratory at Martin Marietta, these costs would approximately equal the average for 449 ship sets.

CONCLUSIONS & RECOMMENDATIONS

The conclusions of this study are:

- The development of composite tubing for flight usage is near completion.
- Composite tubing can reduce the weight of the Space Shuttle External Tank by 620 kg (1360 lb) per tank.
- A 620 kg (1360 lb) weight saving can reduce the Space Shuttle total program cost by \$18,374,000, based on a cost of \$66 per kilogram launch weight, and 449 vehicles (620 kg saved per vehicle x \$66/kg x 449 vehicles = \$18,373,080). When the added costs of producing composite tubing are included a net cost reduction of \$7,300,000 results. These conclusions are based on overwrap being done by Martin Marietta manufacturing and on the quote from Vendor 1 for the thin metal tubing. If the Vendor 2 quote for thin metal tubing is used the total program costs for all-metal and composite tubing is approximately equal.

In summary, it is concluded that the economics of using composite tubing on the Space Shuttle external tank are sufficiently favorable to warrant more detailed investigation and study and performance of the following tasks is recommended to further refine the costs and weight analysis and to further demonstrate the technical integrity of composite tubing.

- Aluminum to Stainless Steel Joints. - The use of conoseal flanges was assumed for weight and cost data in this study. It is not likely that conoseals will be used in cryogenic systems on Space Shuttle. Thus it is recommended that weight and cost data be developed for the type of flange which will be used.
- Minimum Gage. - The 0.117 cm (0.046 in.) minimum gage used in this study is based on informal information from NASA. This requirement stems from Saturn experience where line damage was a significant problem. It is recommended that a minimum gage be firmly established with NASA and any adjustments required factored into the trade study.
- Additional Weight Reduction. - An additional 90 kg (200 lb) weight per ship set can be saved by the use of a low density 0.0015 kg/cm^3 (0.055 lb/in.^{3}) composite. Approximately 34 kg (75 lb) of additional weight per ship set can be saved by increasing all line lengths to 6 meters (20 feet), where the configuration permits, thus reducing the number of end fittings. It is recommended that the costs of low density composites in the quantities required for Space Shuttle be determined and that manufacturing techniques be studied for the production of 6 meter (20 ft) long small diameter lines.

- Design. - It is recommended that detail design layouts, including supports, expansion joints, gimbals, etc., be made for composite tubing These layouts will then form the basis for a more refined weight/cost analysis.

- Qualification. - It is recommended that a propulsion system qualification test plan be developed and coordinated with NASA, and a complete system using composite tubing be designed, built and qualification tested.

- Overwrap Tooling. - The cost estimates reflected herein include 35 man years of recurring tooling labor and 10.6 man years of non-recurring tooling. This is probably more than required. It is recommended that this task be studied further to obtain a more realistic tooling cost.

APPENDIX G

DATA ACQUISITION EQUIPMENT LIST

APPENDIX G

DATA ACQUISITION EQUIPMENT LIST

1. Recorders

a) Sanborn 6 Channel

Model: 156-100BW

Chart Speeds: 0.25, 0.5, 1, 2.5, 5, 10, 25, 50, and 100 mm/sec.

Frequency Response: DC to 100 Hz with 3dB down at 10 divisions P-P amplitude.

Rise Time: 5 milliseconds

Linearity: Essentially perfect over the middle 40 divisions of the 50 division chart. Maximum error over entire 50 divisions is less than 0.5 division.

Sensitivity: Approximately 0.5 V/cm of deflection.

Drift: Less than 0.5 division per hour.

b) Honeywell 24 Channel, Multi-point

Model: Electronik 153

Chart Speed: 1 in/min (2.54 cm/min)

Balance Speed: 4.5 seconds

Printing Speed: 5.0 seconds

Reference Junction: Copper-Constantan

2. Digital Instruments

a) Dana Digital Voltmeter

Model: 5740

Range: Ranges covering 10 millivolt DC to 1000.00 volt DC

Resolution: From 0.1 micro volts DC to 10 millivolts DC.

Short Term Accuracy: $\pm$ 0.001% of full scale on all ranges.

Digitizing Time: 13 ms constant range and polarity.

b) Honeywell DC Potentiometric

Model: 852

Range: 1KV, 100V, 10V, and 1V.

Resolution: 0.001% of full scale on all ranges.

Short Term Stability: $\pm$ 0.005% per day, non-cumulative.

c) Leeds & Northrup Potentiometer

Model: 8686

Range: -10.100 to +1010.000 mv, +1010.000 to 1020.000 mv

Resolution: 1 microvolt

3. Signal Amplifiers

Dana Differential Amplifier

Model: 2860 (with filtering)

Linearity: DC to 2 KHZ $\pm$ 0.01%

Range: 1 to 2500 gain $\pm$ 0.01%

4. Leak Detector

Consolidated Electrodynamics, Helium Mass Spectrometer, Model 24-120

SENSOR OR TRANSDUCER LIST

1. <u>Pressure Transducers</u>

a) Taber Instruments Corporation - Model 206

2. <u>Strain Gages</u>

a) Automation Industries

Model C9-125-R2T Rosette

Model S741-R2T-300 Rosette

b) Baldwin - Lima - Hamilton

Type C-8

Type DLB-MK35-4A-S13

3. <u>Accelerometers</u>

Endevco, Model 2222B

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